Deep Underground Science and Engineering Workshop

Berkeley, CA

August 11, 2004

Neutrinos

Preview of the APS Neutrinos Study
Connections to a National Underground Laboratory

Stuart Freedman
University of California at Berkeley

The DNP/DPF/DAP/DPB

Joint Study on the Future of Neutrino Physics

The Neutrino Matrix

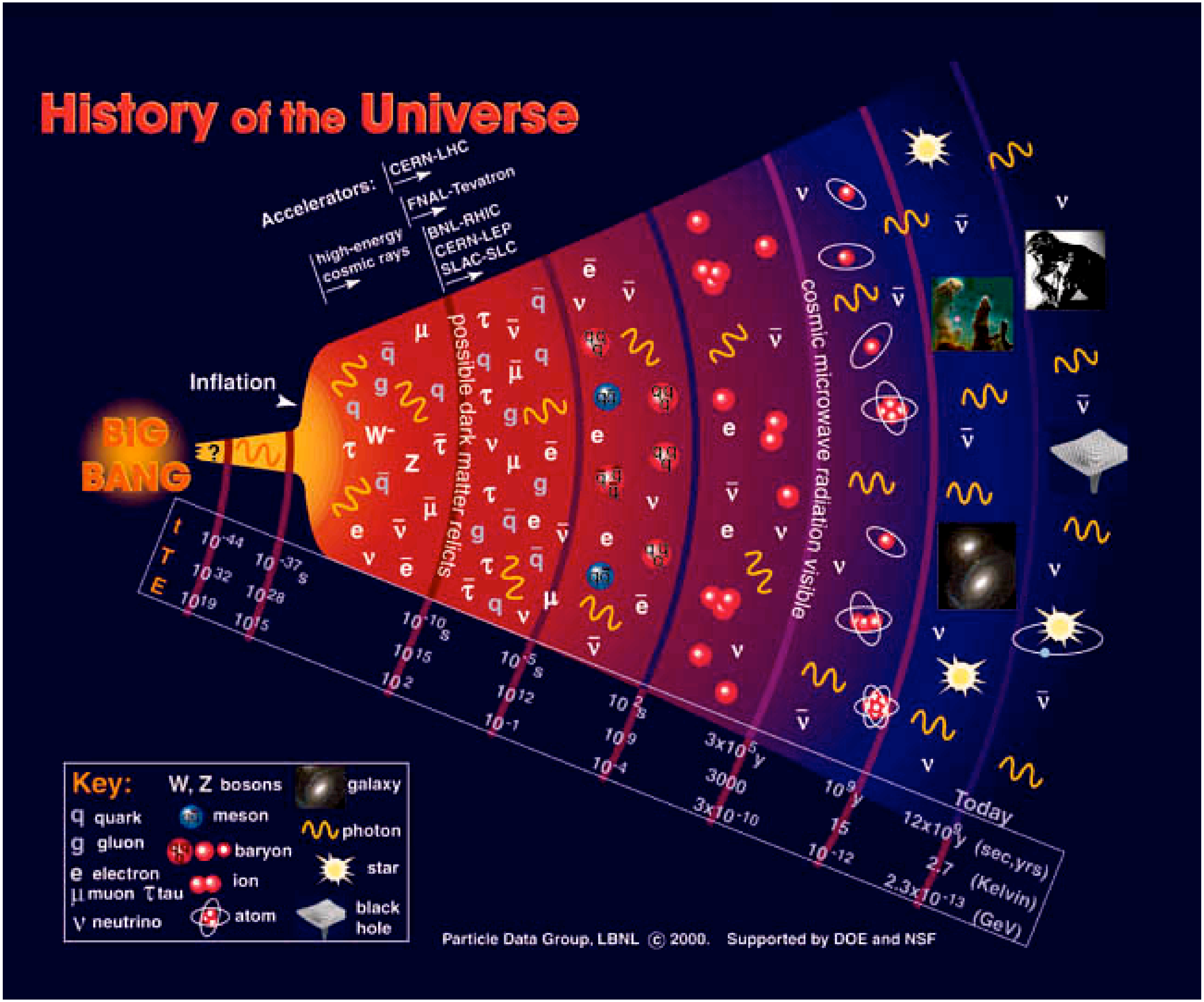
The Charge

The APS Divisions of Particles and Fields and of Nuclear Physics, together with the APS Divisions of Astrophysics and the Physics of Beams, is organizing a year-long Study on the Physics of Neutrinos, beginning in the fall of 2003. The Study is in response to the remarkable recent series of discoveries in neutrino physics and to the wealth of experimental opportunities on the horizon. It will build on the extensive work done in this area in preparation for the 2002 long range plans developed by NSAC and HEPAP, as well as more recent activities, by identifying the key scientific questions driving the field and analyzing the most promising experimental approaches to answering them. The results of the Study will inform efforts to create a scientific roadmap for neutrino physics.

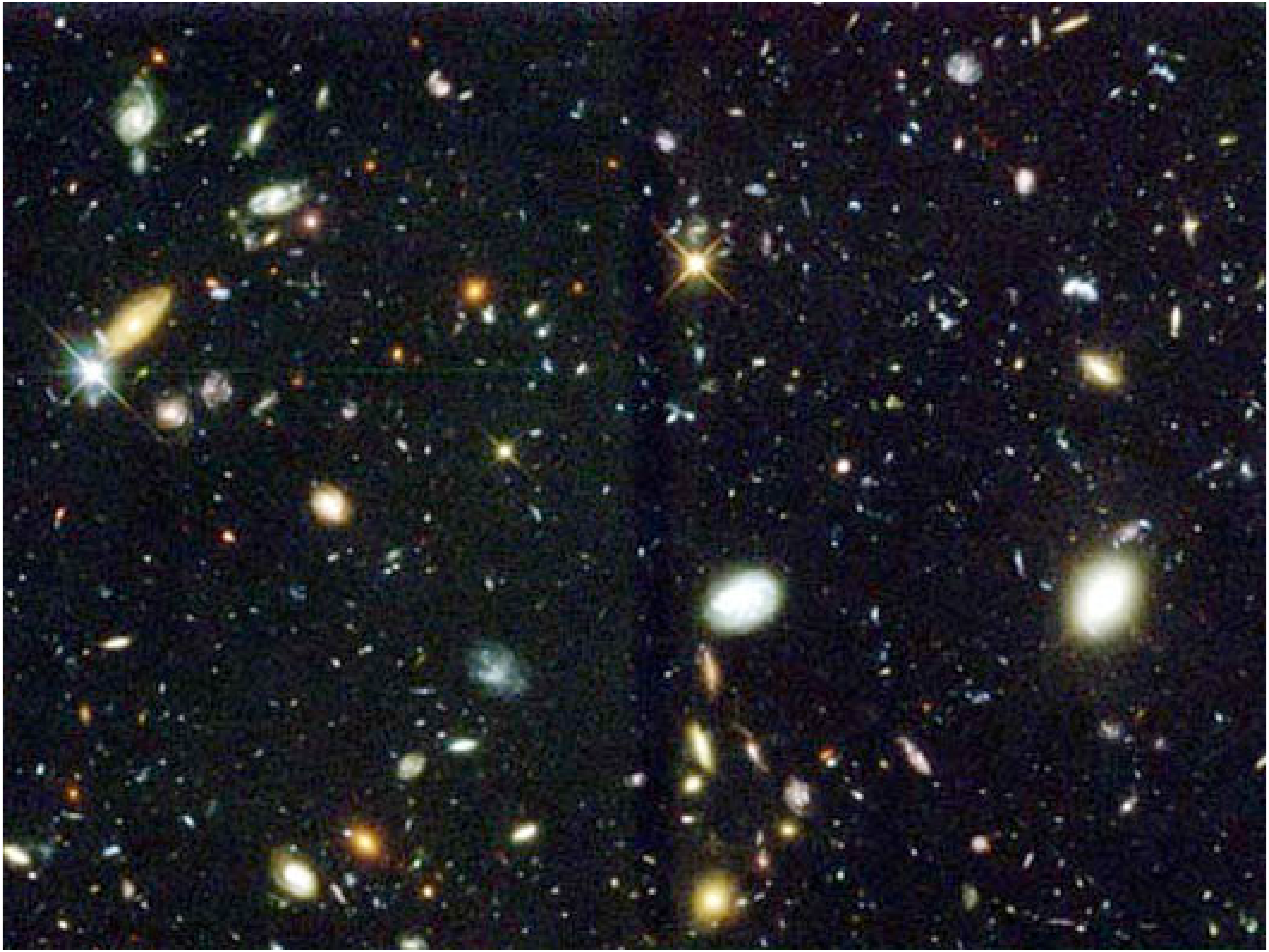
The Study is being carried out by four APS Divisions because neutrino physics is inherently interdisciplinary in nature. The Study will consider the field in all its richness and diversity. It will examine physics issues, such as neutrino mass and mixing, the number and types of neutrinos, their unique assets as probes of hadron structure, and their roles in astrophysics and cosmology. It will also study a series of experimental approaches, including long and short baseline accelerator experiments, reactor experiments, nuclear beta-decay and double beta-decay experiments, as well as cosmic rays and cosmological and astrophysical observations. In addition, the study will explore theoretical connections between the neutrino sector and physics in extra dimensions or at much higher scales.

The Study will be led by an Organizing Committee and carried out by Working Groups. The Organizing Committee will function as an interdisciplinary team, reporting to the four Divisions, with significant international participation. The Study will be inclusive, with all interested parties and collaborations welcome to participate. The final product of the Study will be a book (or e-book) containing reports from each Working Group, as well as contributed papers by the Working Group participants. The Organizing Committee and Working Group leaders will integrate the findings of the Working Groups into a coherent summary statement about the future. The Working Groups will meet as necessary, with a goal of producing the final report by August 2004.

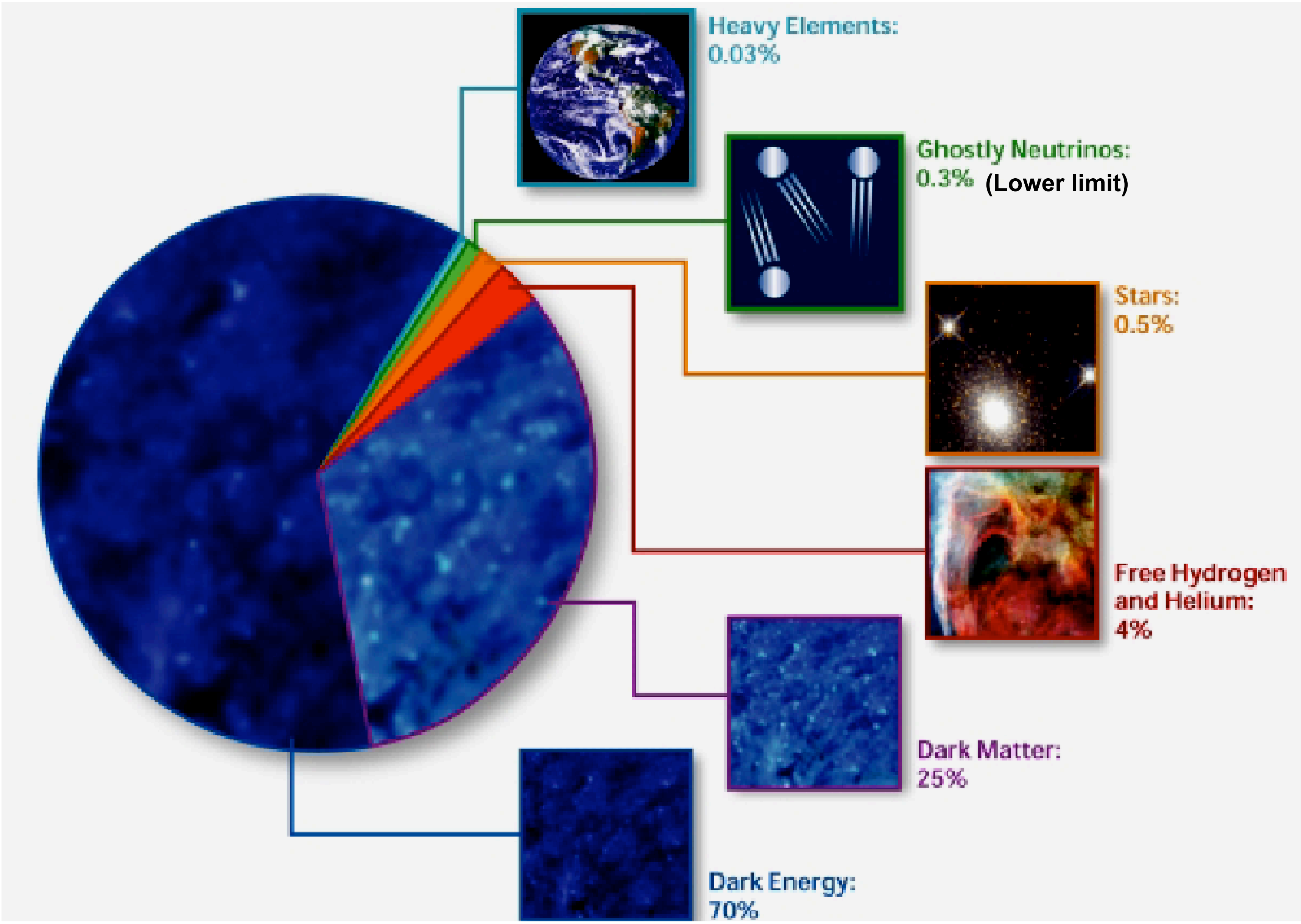
The overarching purpose of the Study is for a diverse community of scientists to examine the broad sweep of neutrino physics, and if possible, to move towards agreement on the next steps towards answering the questions that drive the field. The Study will lay scientific groundwork for the choices that must be made during the next few years.



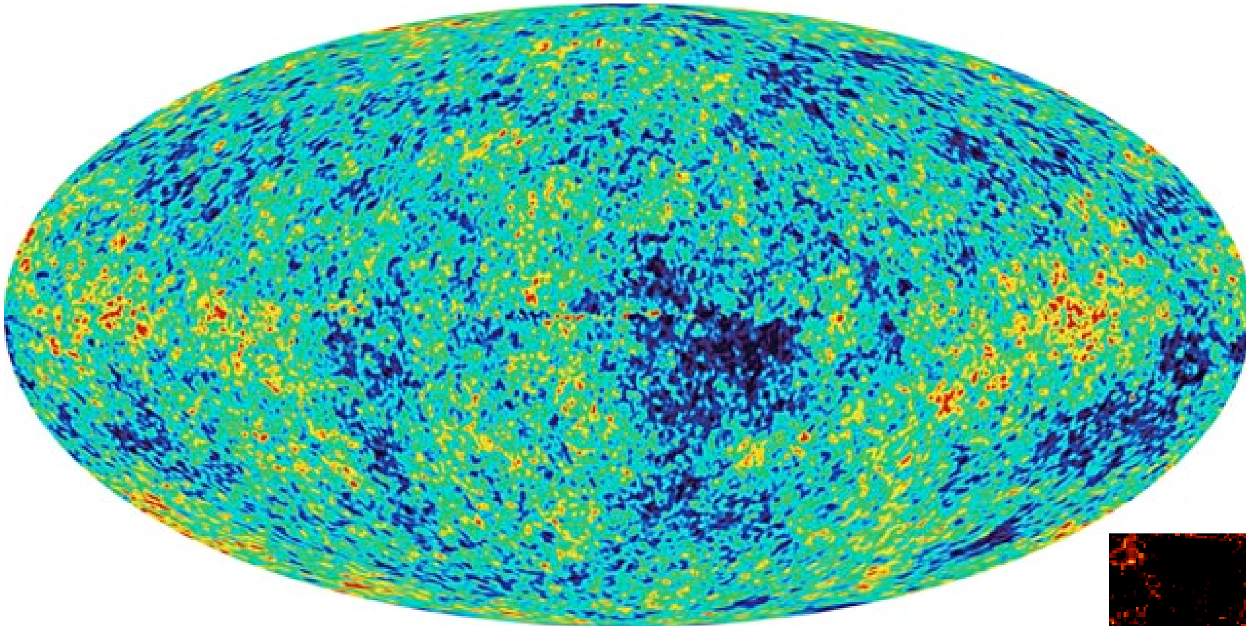
History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relics
cosmic microwave radiation visible
t
T
E
10^{-44}
10^{32}
10^{19}
10^{-37}s
10^{28}
10^{15}
10^{-10}s
10^{15}
10^{2}
10^{-5}s
10^{12}
10^{-1}
10^{2}s
10^{9}
10^{-4}
$3x10^{5}$y
3000
$3x10^{-10}$
10^{9}y
15
10^{-12}
Today
$12x10^{9}$y (sec,yrs)
2.7 (Kelvin)
$2.3x10^{-13}$ (GeV)
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
galaxy
photon
star
black hole
Particle Data Group, LBNL © 2000. Supported by DOE and NSF



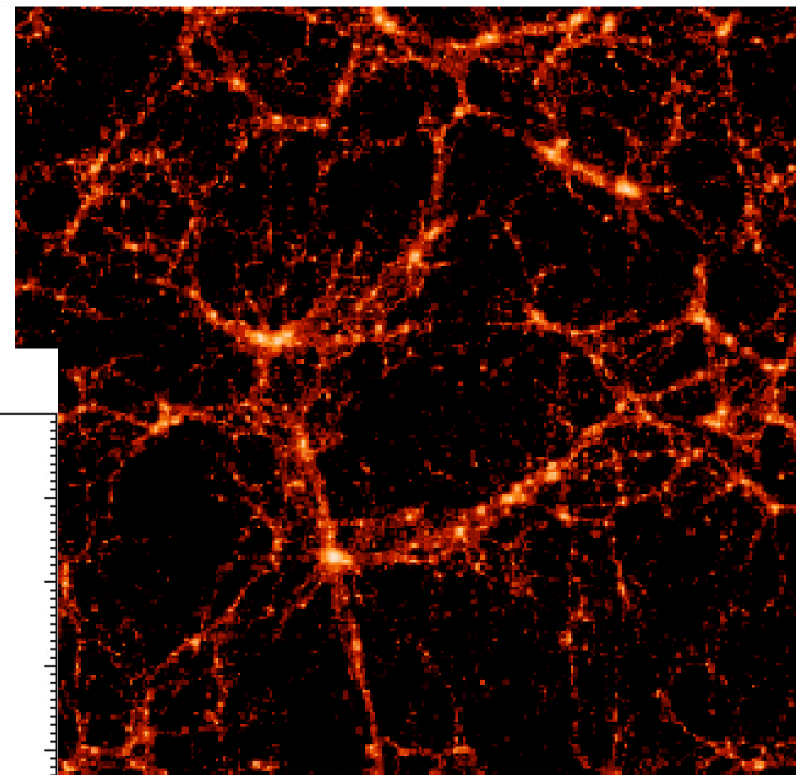
What's the Matter?



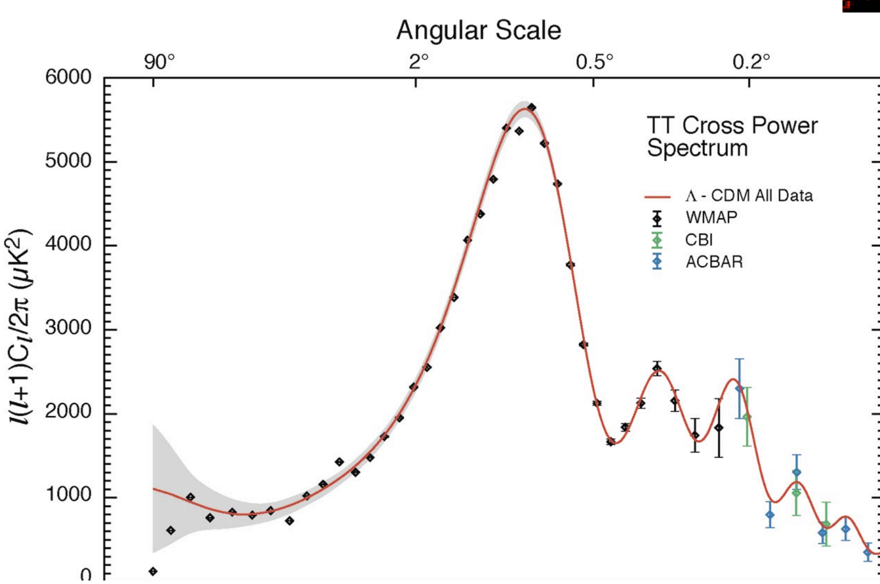
Evolution from last scattering



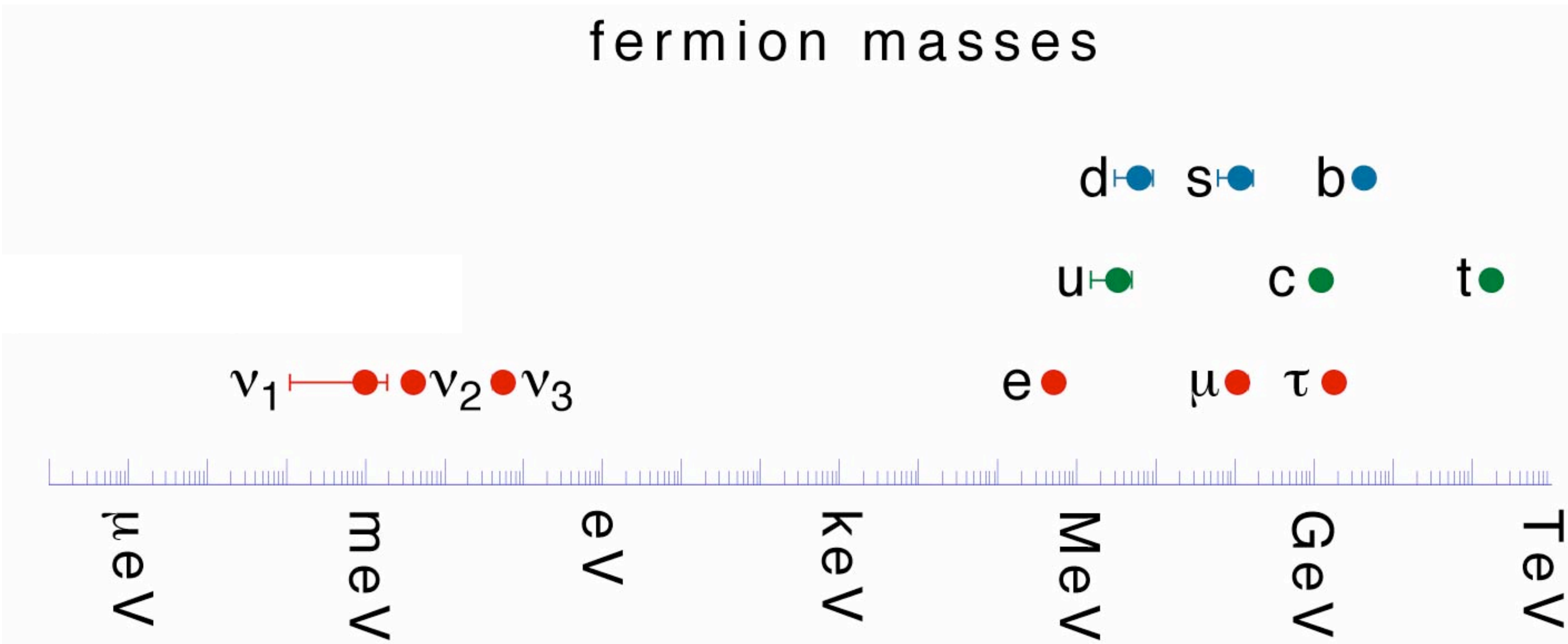
Cosmic Microwave Background (WMAP)



Large Scale Structure

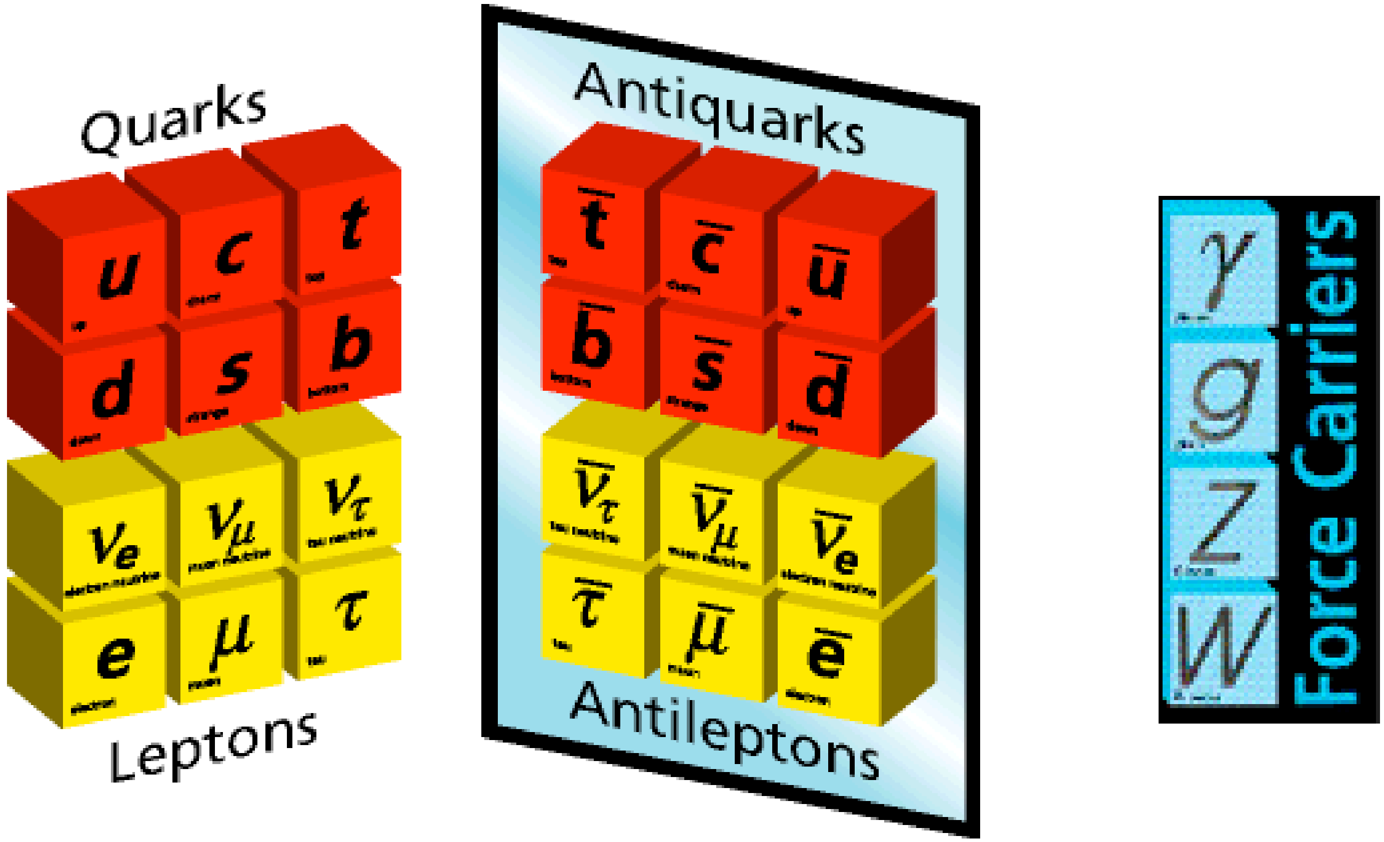


Problem!



hierarchy

The Standard Model



This picture needs revision

APS Neutrino Study Organization

Chairpersons

Stuart Freedman, Boris Kayser

Organizing Committee

Janet Conrad, Guido Drexlin,
Belen Gavela, Takaaki Kajita,
Paul Langacker, Keith Olive,
Bob Palmer, Georg Raffelt,
Hamish Robertson, Stan Wojcicki,
Lincoln Wolfenstein

Working Groups

Solar and Atmospheric Neutrino Experiments

John Bahcall and Josh Klein

Reactor Neutrino Experiments

Gabriela Barenboim and Ed Blucher

Superbeam Experiments and Development

Bill Marciano and Doug Michael

Neutrino Factory and Beta-Beam Experiments and Development

Stephen Geer and Michael Zisman

Neutrinoless Double Beta Decay and Direct Searches for Neutrino Mass

Steve Elliott and Petr Vogel

What Cosmology/Astrophysics and Neutrino Physics can Teach Each Other

Steve Barwick and John Beacom

Theory Discussion Group

Rabi Mohapatra

Workshop to kick off the APS Neutrino Study

The APS Divisions of Particles and Fields and of Nuclear Physics, together with the Divisions of Astrophysics and the Physics of Beams, are sponsoring a year-long Study on the Physics of Neutrinos, beginning in the fall of 2003.

December 13-14, 2003

Argonne National Laboratory

This is a temporary web page for the workshop to kick off the Neutrino Study. The Workshop will be held December 13-14, 2003 (Saturday-Sunday) at Building 36 Argonne National Laboratory

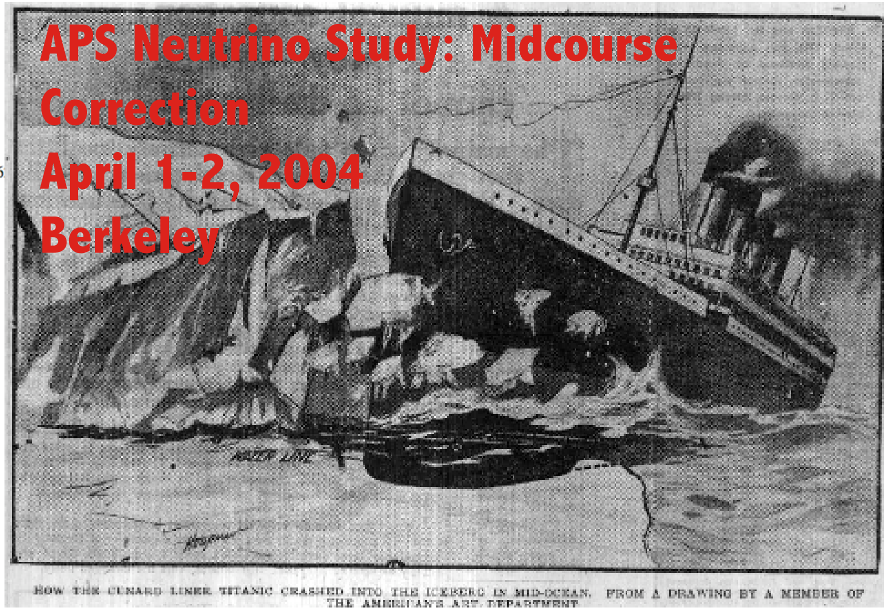
We are pleased to announce a workshop on Neutrino Phyics in the High Energy Physics Division at Argonne National Laboratory from December 13-14, 2003. After consideration of other sites, the workshop will now be held at Argonne National Laboratory.

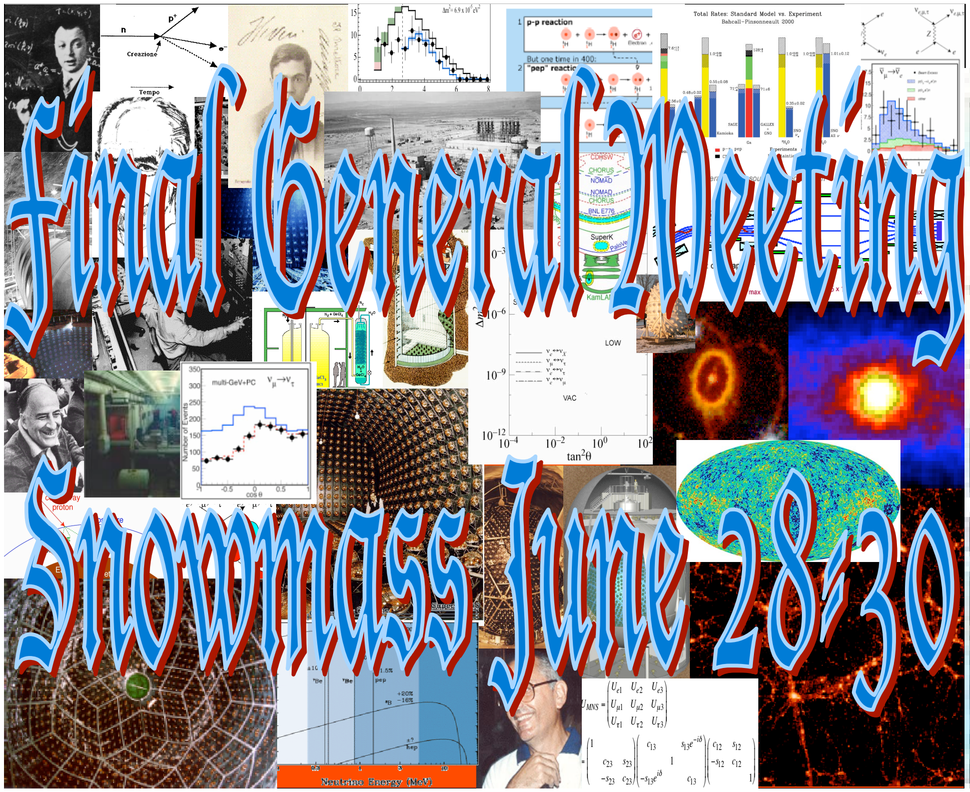
Participants will need to register in advance in order to prepare a gate pass. See below.

The aim of the workshop is given below along with the Charge on the APS study.

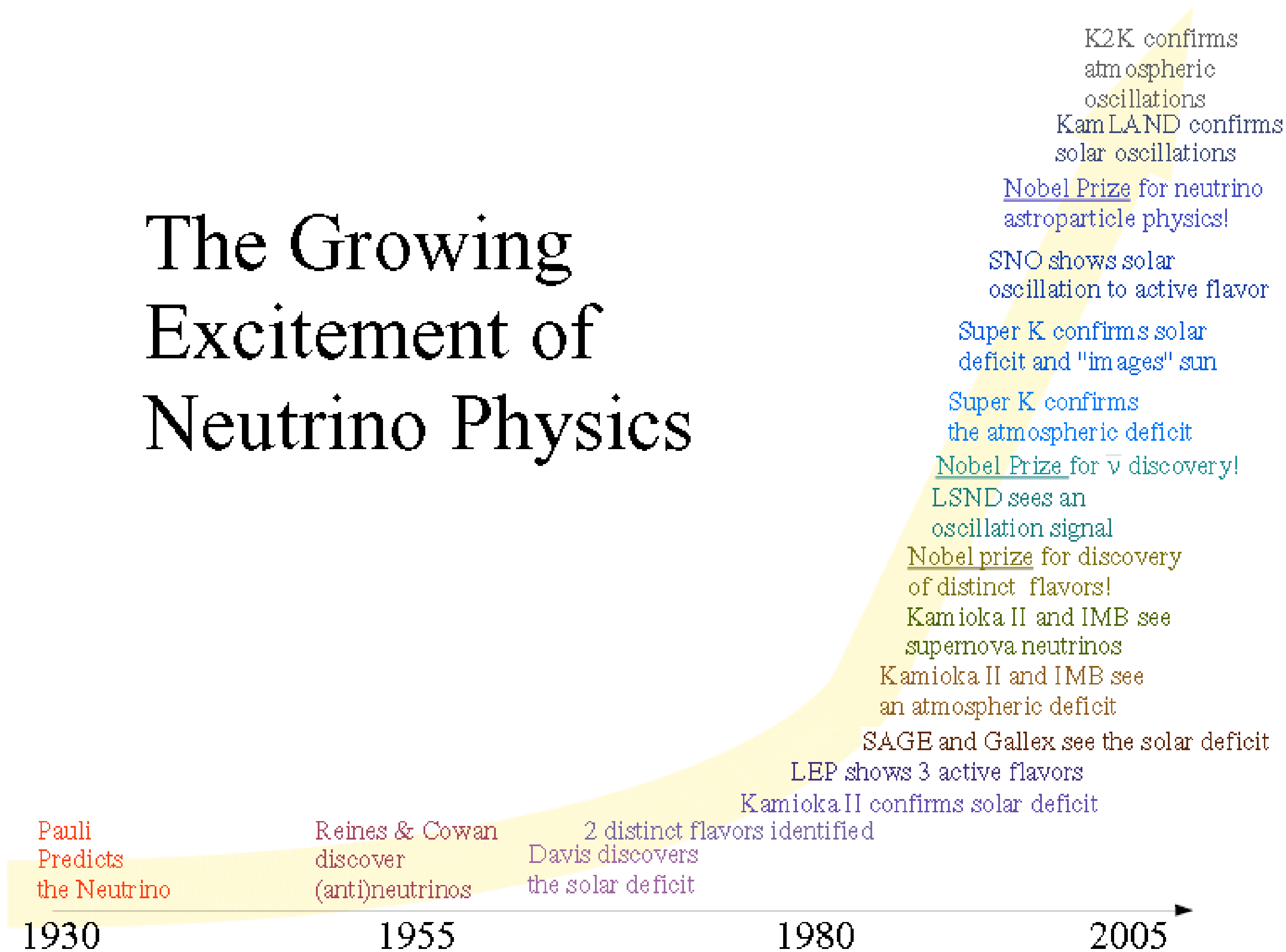
Workshop Links

- Information for attendees
- Registration Form (closed)
- Program (including transparencies)
- Working Groups
- Link for those who want to participate in the study but can't come to the workshop
- List of attendees as of December 12, 2003



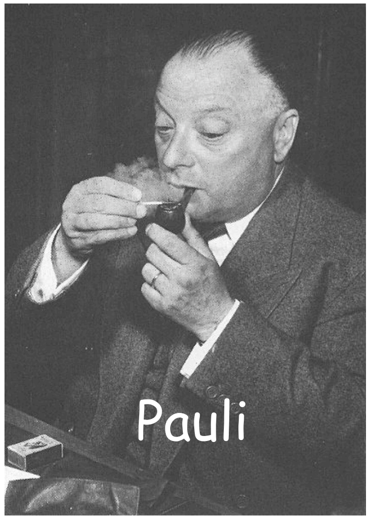


The Growing Excitement of Neutrino Physics



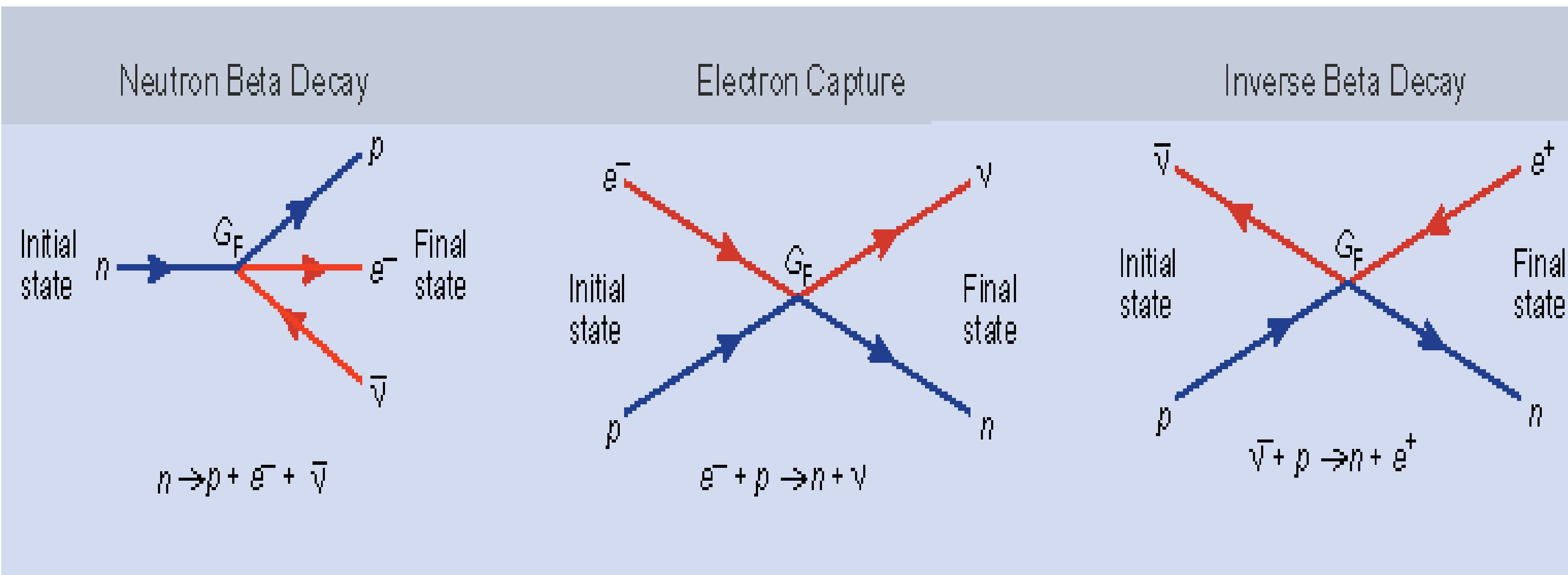
Preliminary

APS Neutrino Study



Inventor

Developer



Previously Rejected By Nature

ANNO IV - VOL. II - N. 12 QUINDICINALE 31 DICEMBRE 1933 - XII

LA RICERCA SCIENTIFICA

ED IL PROGRESSO TECNICO NELL'ECONOMIA NAZIONALE

Tentativo di una teoria dell'emissione dei raggi "beta"

Nota del Prof. ENRICO FERMI

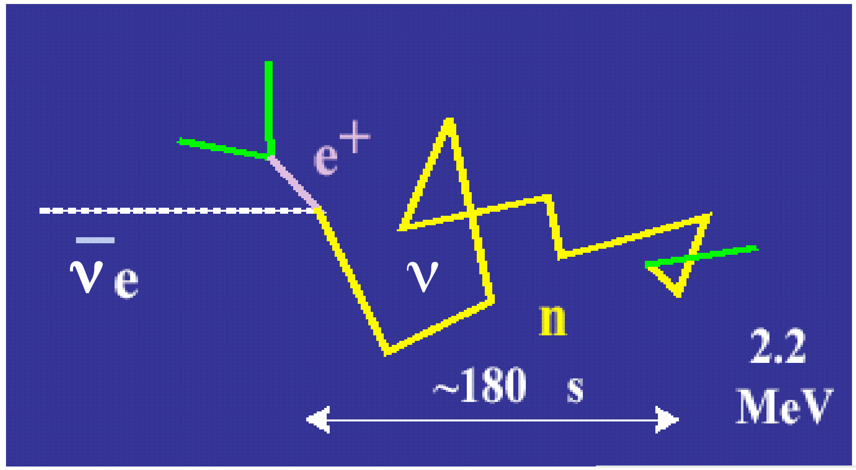
Riassunto: Teoria della emissione dei raggi β delle sostanze radioattive, fondata sull'ipotesi che gli elettroni emessi dai nuclei non esistano prima della disintegrazione ma vengano formati, insieme ad un neutrino, in modo analogo alla formazione di un quanto di luce che accompagna un salto quantico di un atomo. Confronto della teoria con l'esperienza.

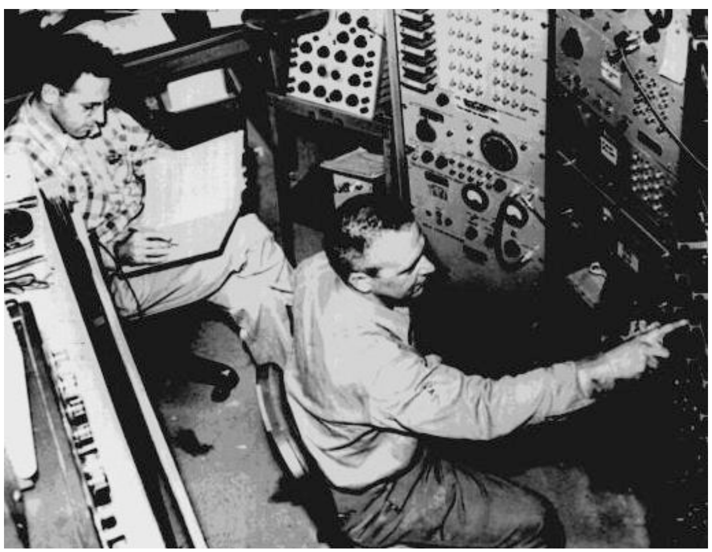
Mi propongo di esporre qui i fondamenti di una teoria dell'emissione dei raggi β che, benchè basata sopra ipotesi delle quali manca al momento presente qualsiasi conferma sperimentale, sembra tuttavia capace di dare una rappresentazione abbastanza accurata dei fatti e permette una trattazione quantitativa del comportamento degli elettroni nucleari che, se pure le ipotesi fondamentali della teoria dovessero risultare false, potrà in ogni caso servire di utile guida per indirizzare le ricerche sperimentali.

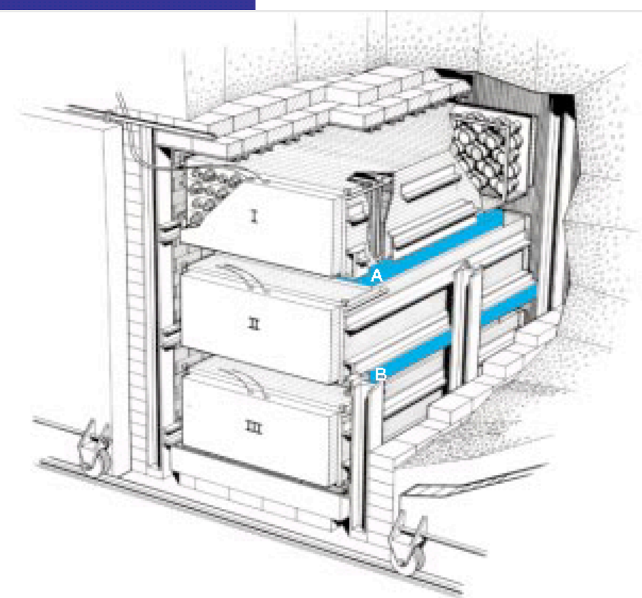
E' ben noto che nel cercare di costruire una teoria dei raggi β si incontra una prima difficoltà dipendente dal fatto che i raggi β escono dai nuclei radioattivi con una distribuzione continua di velocità che si estende fino a una certa velocità massima; il che a prima vista non sembra conciliabile col principio della conservazione dell'energia. Una possibilità qualitativa di spiegare i fatti senza dover abbandonare il principio della conservazione dell'energia consiste, secondo Pauli, nell'ammettere l'esistenza del così detto «neutrino», e cioè di un corpuscolo elettricamente neutro con massa dell'ordine di grandezza di quella dell'elettrone o minore. In ogni disintegrazione β si avrebbe emissione simultanea di un elettrone e di un neutrino: e l'energia liberata nel processo si ripartirebbe comunque tra i due corpuscoli in modo appunto che l'energia dell'elettrone possa prendere tutti i valori da 0 fino ad un certo massimo. Il neutrino d'altra parte, a causa della sua neutralità elettrica e della piccolissima massa, avrebbe un potere penetrante così elevato da sfuggire praticamente ad ogni attuale metodo di osservazione. Nella teoria che ci proponiamo di esporre ci metteremo dal punto di vista della ipotesi dell'esistenza del neutrino.

First Direct Detection of the Neutrino

$$\bar{\nu}_e + p \rightarrow e^+ + n$$







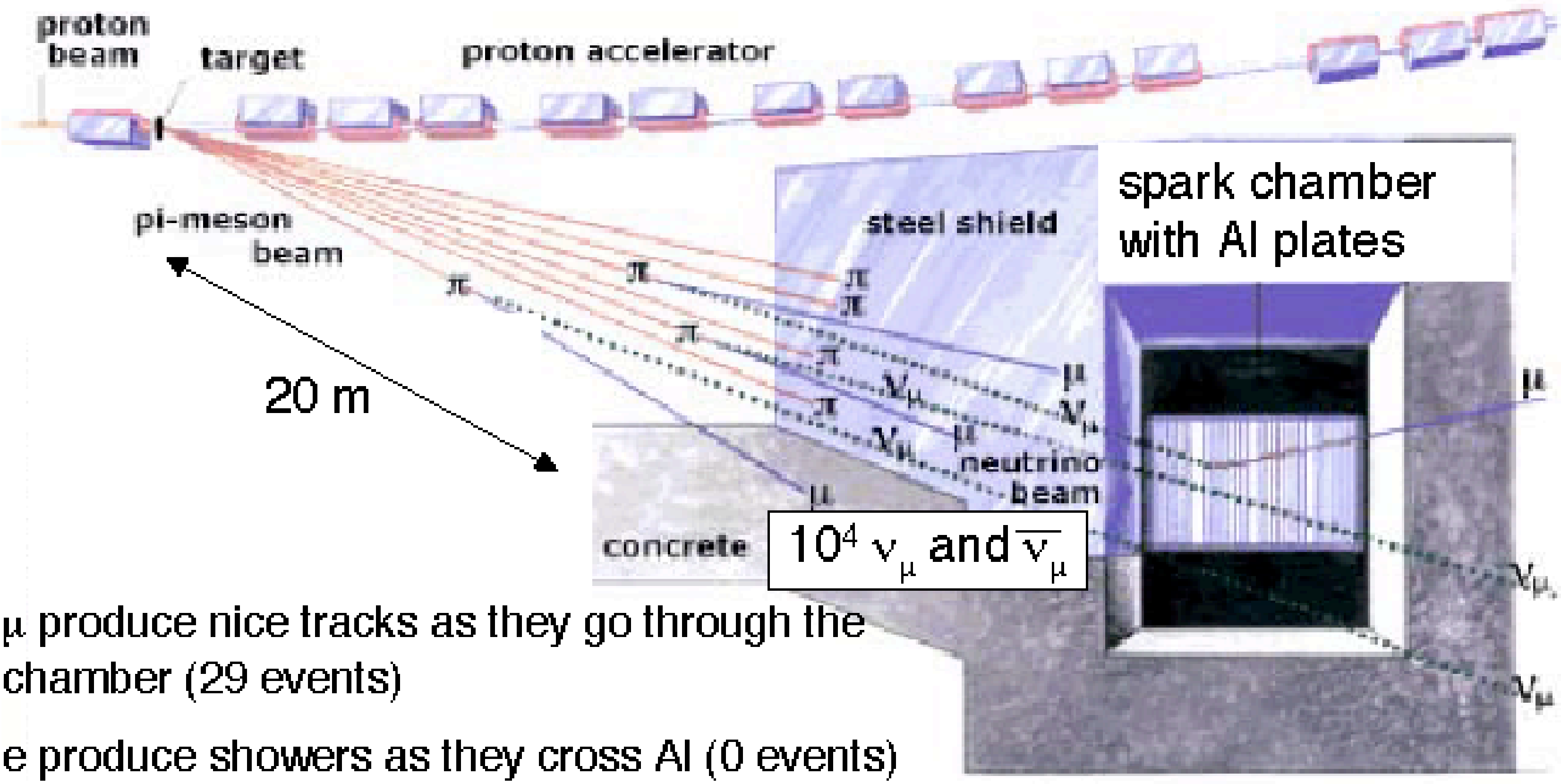
Reines and Cowan 1955

Discovery of Muon Neutrino

1962

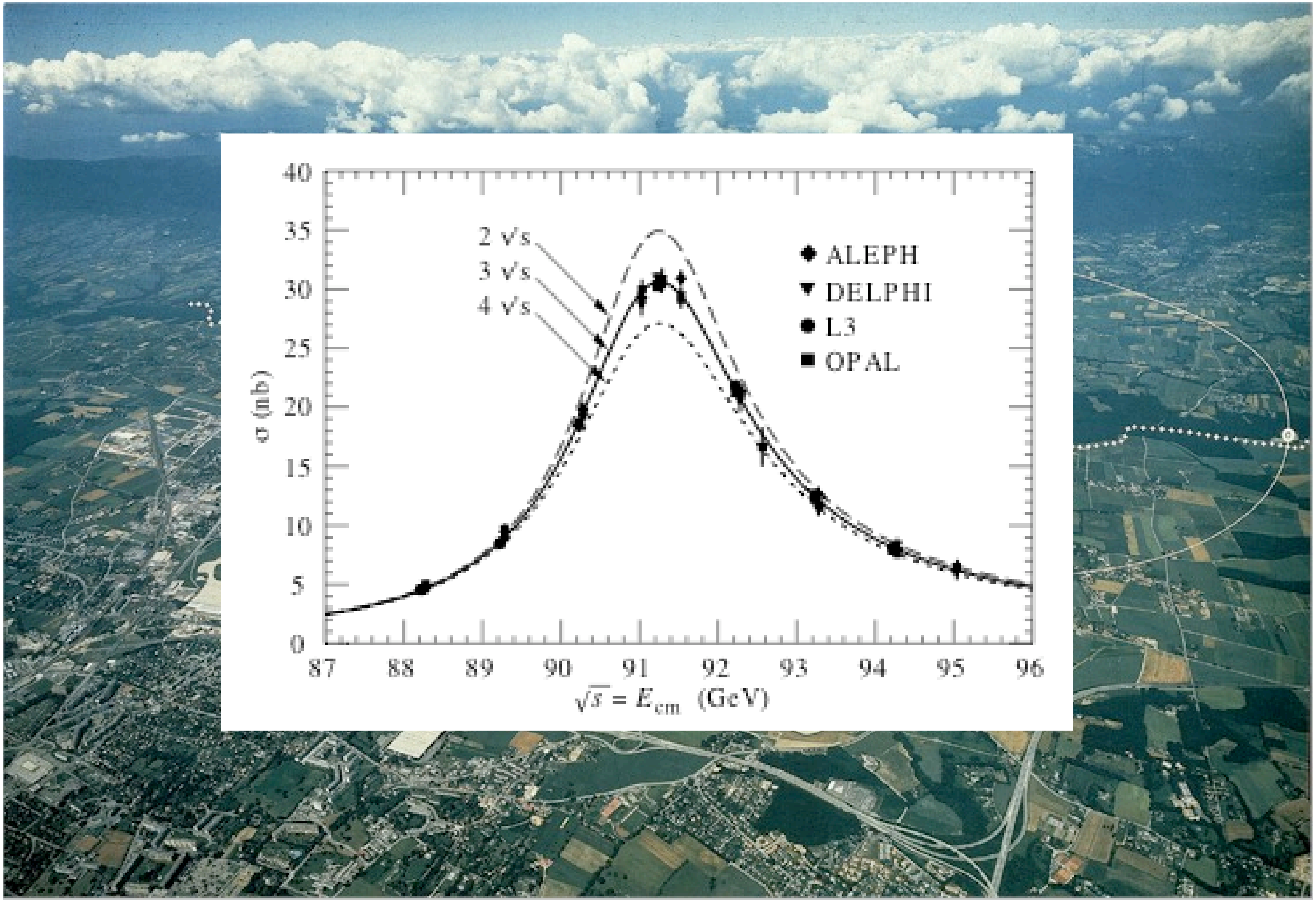
$$\bar{\nu}_\mu + p \rightarrow n + \mu^+$$
$$\nu_\mu + n \rightarrow p + \mu^-$$

Lederman, Schwarts, Steinberger



μ produce nice tracks as they go through the chamber (29 events)

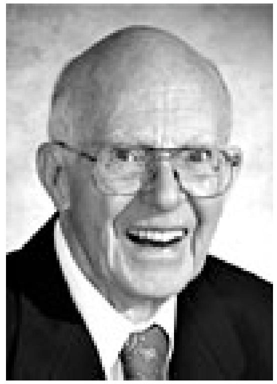
e produce showers as they cross Al (0 events)



40
35
30
25
20
15
10
5
0
σ (nb)
2 √s
3 √s
4 √s
ALEPH
DELPHI
L3
OPAL
87
88
89
90
91
92
93
94
95
96
√s = E_cm (GeV)

CERN

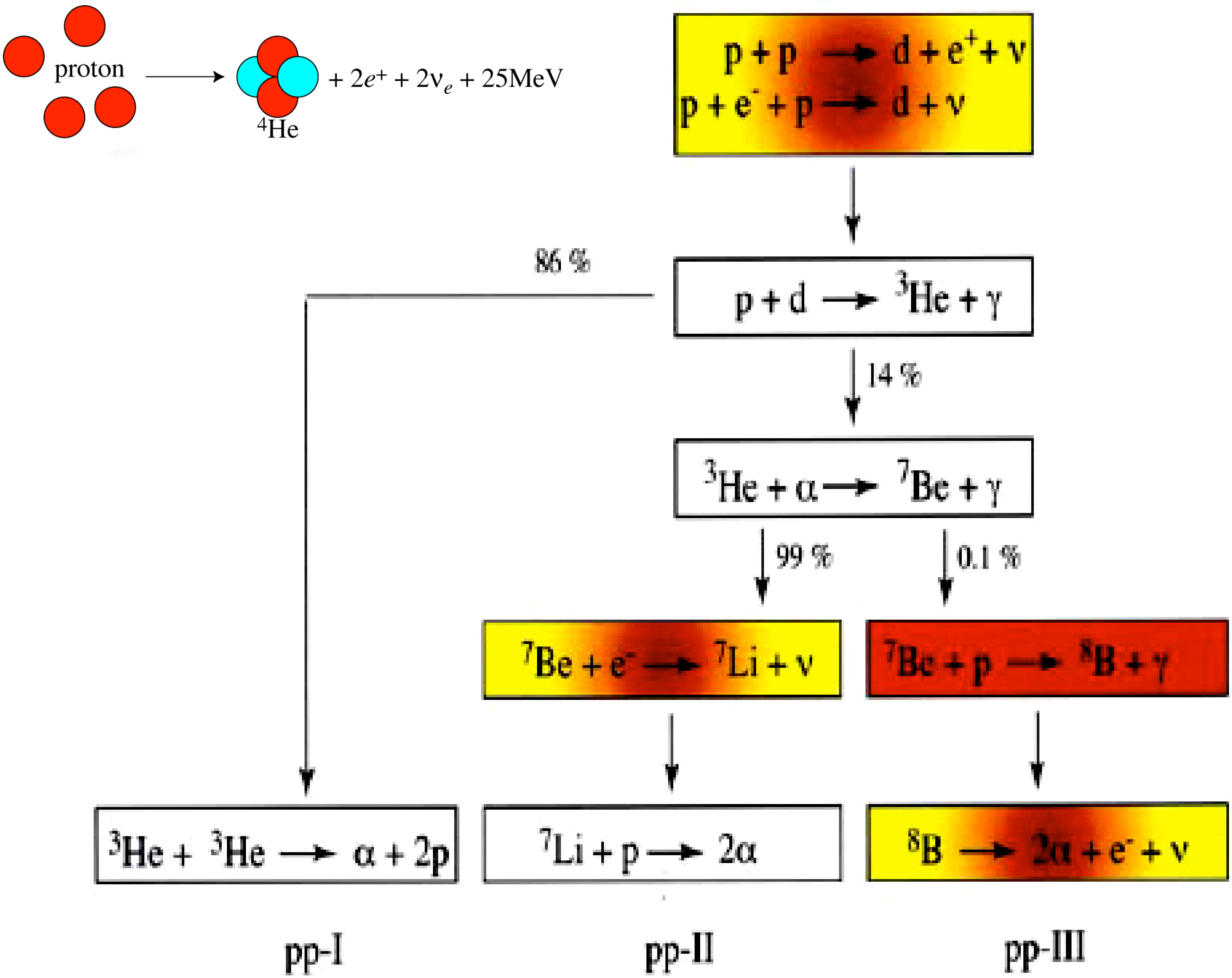
Pioneer of Solar Neutrino Science



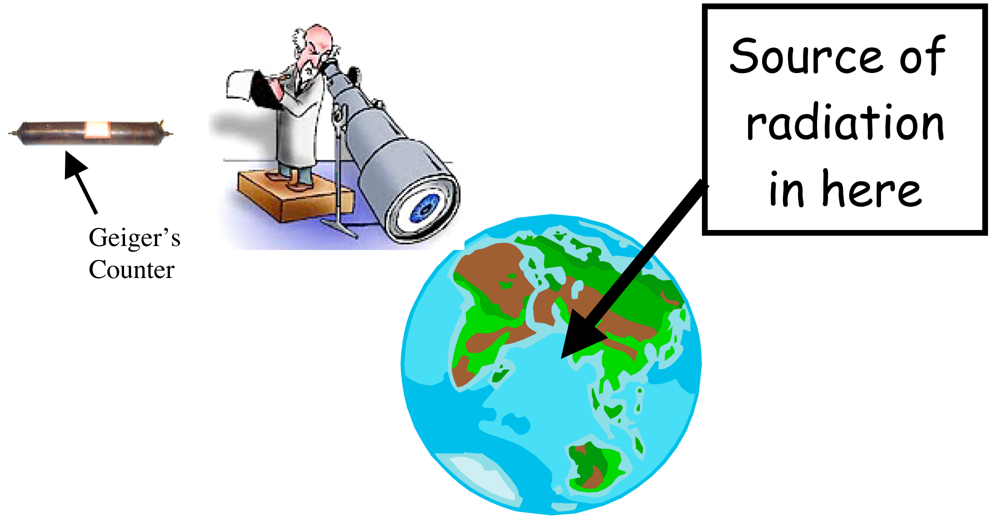
$^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$

1968 First Solar Neutrino Experiment

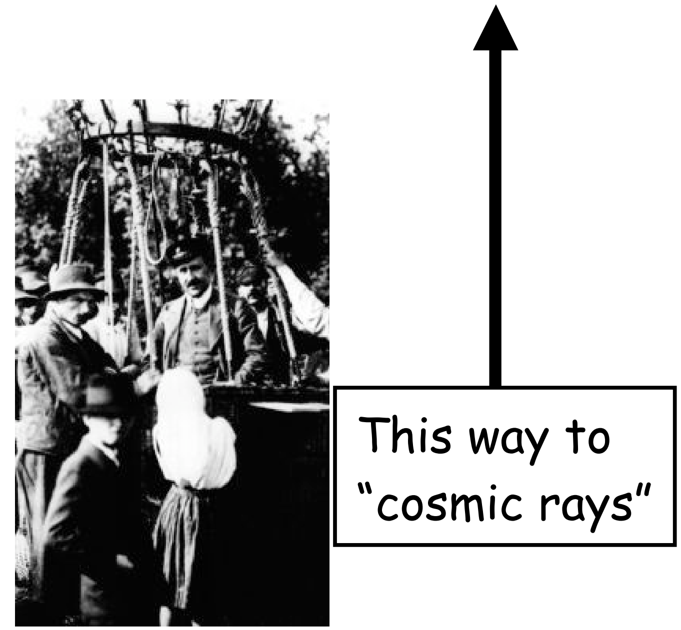
The Sun is Fueled by Nuclear Reactions



Underground Science



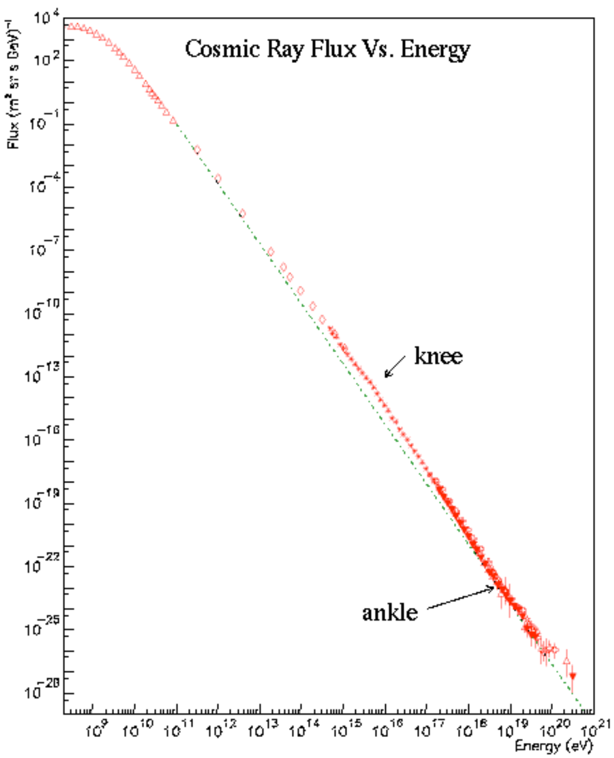
Millikan ~1910



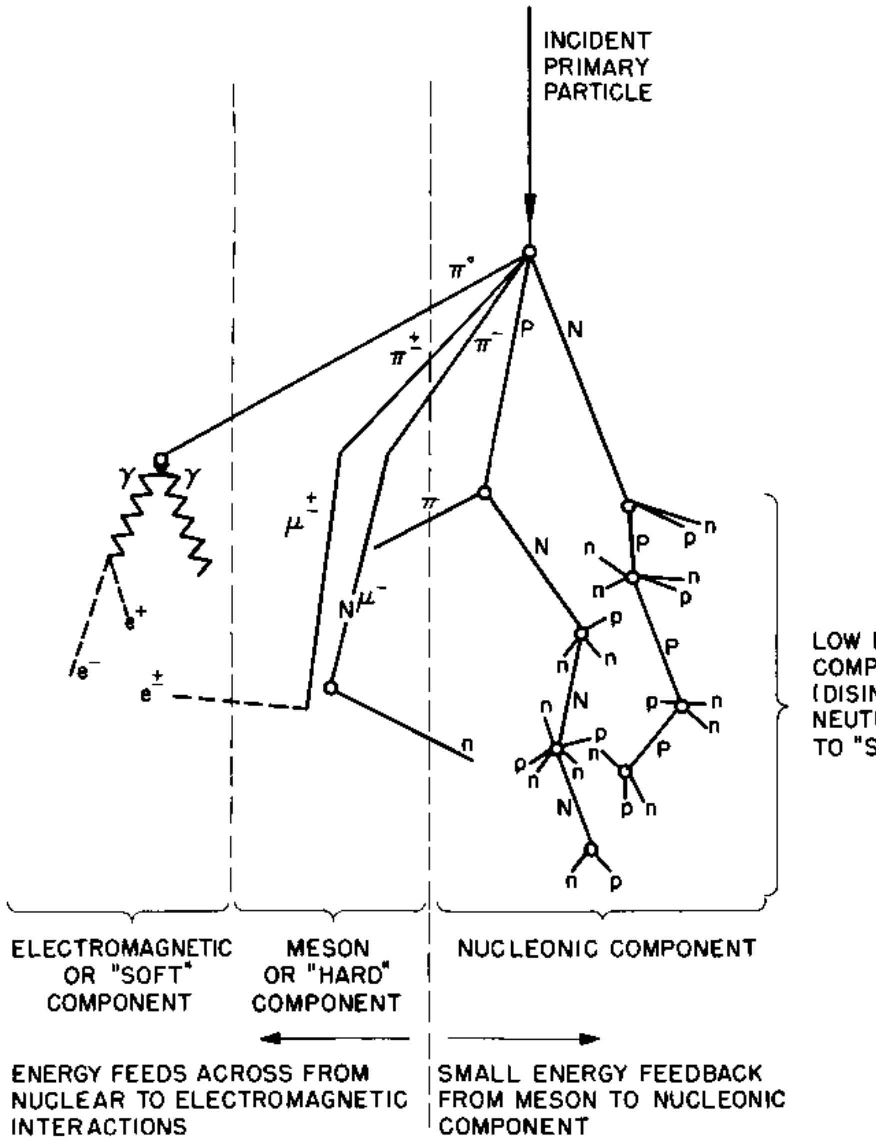
Hess 1912

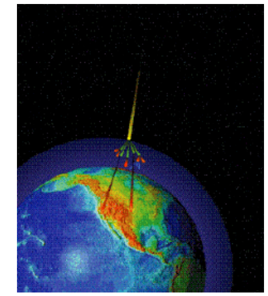
Millikan proposed going underground to disprove Hess' suggestion that radiation from outer space is not the source of unexplained backgrounds on the Earth's surface. Millikan proposed the Earth's core as the source. Millikan went down. Hess went up and discovered the "cosmic rays".

Cosmic Rays



Cosmic Ray Flux vs Energy



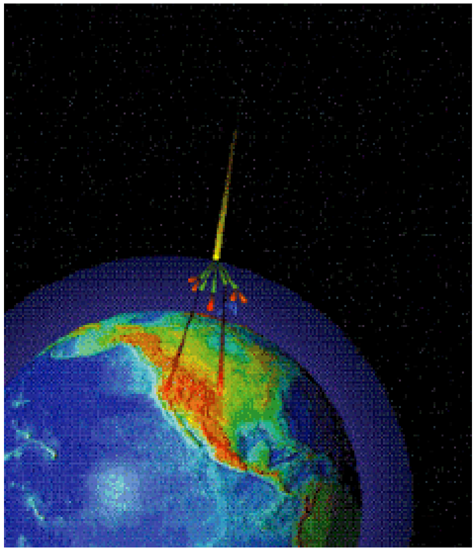


Cosmic Ray Secondaries

(neutrinos not shown)

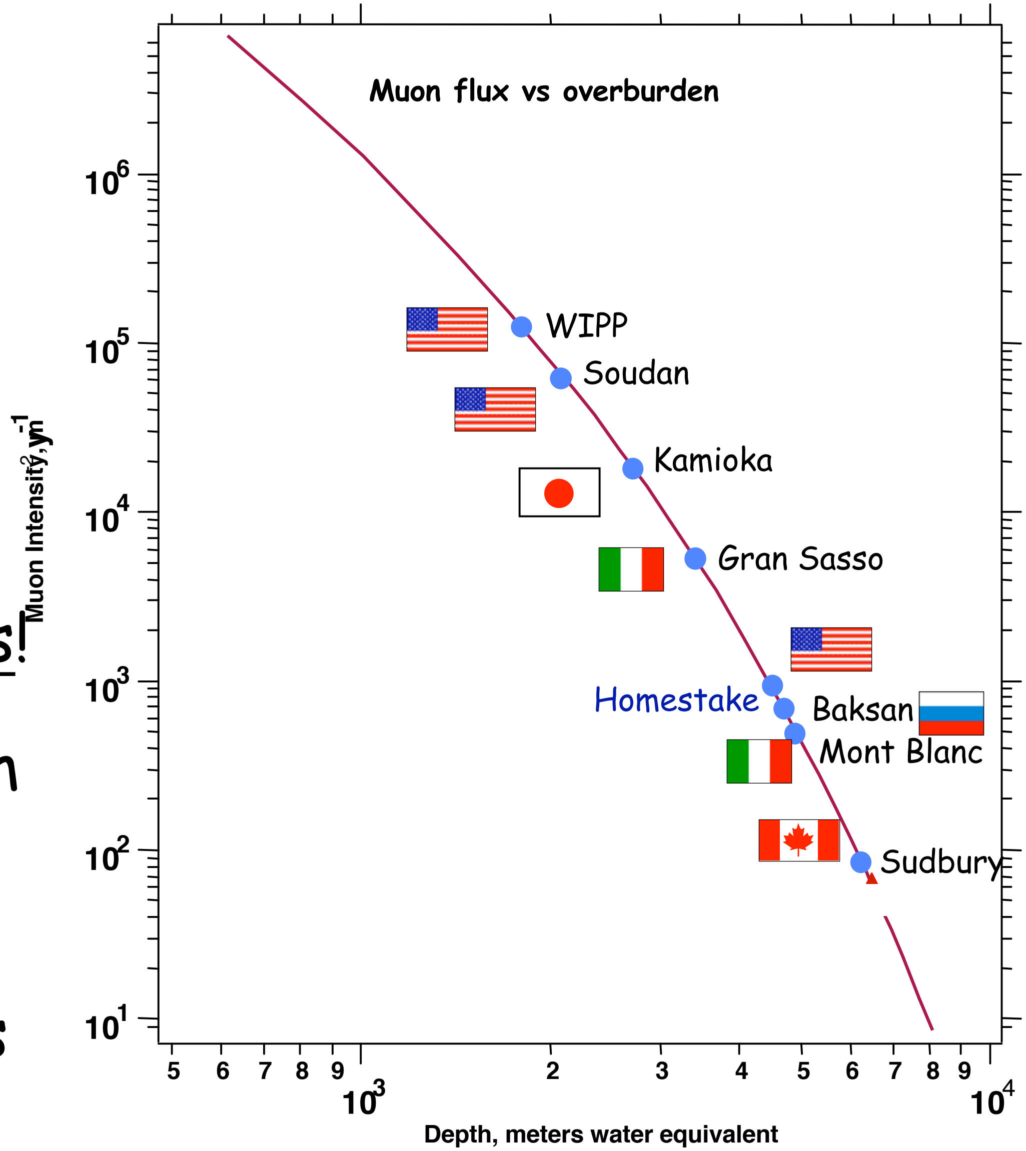
Backgrounds!

Underground!

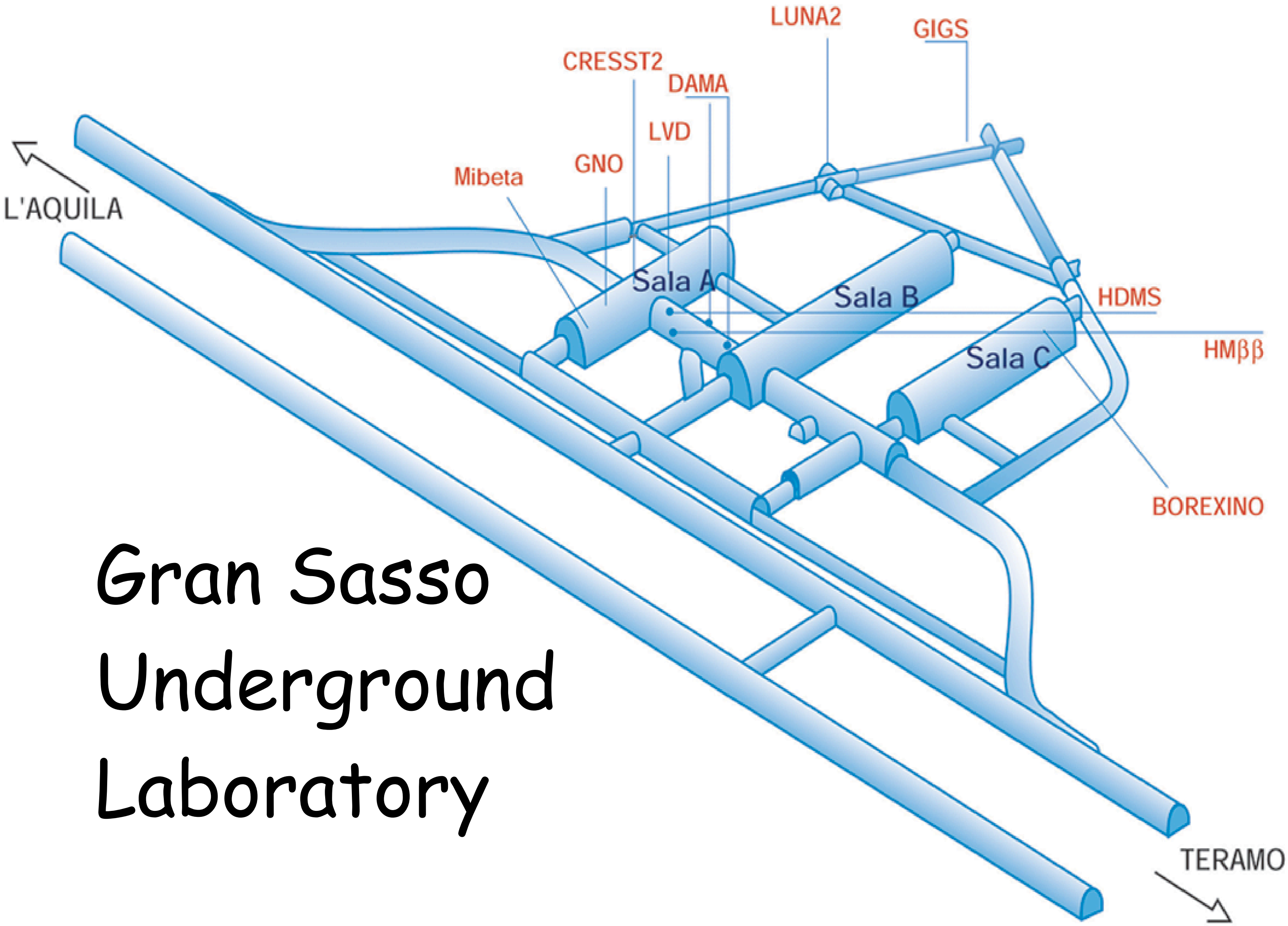


Avoid Atmospheric Muons!

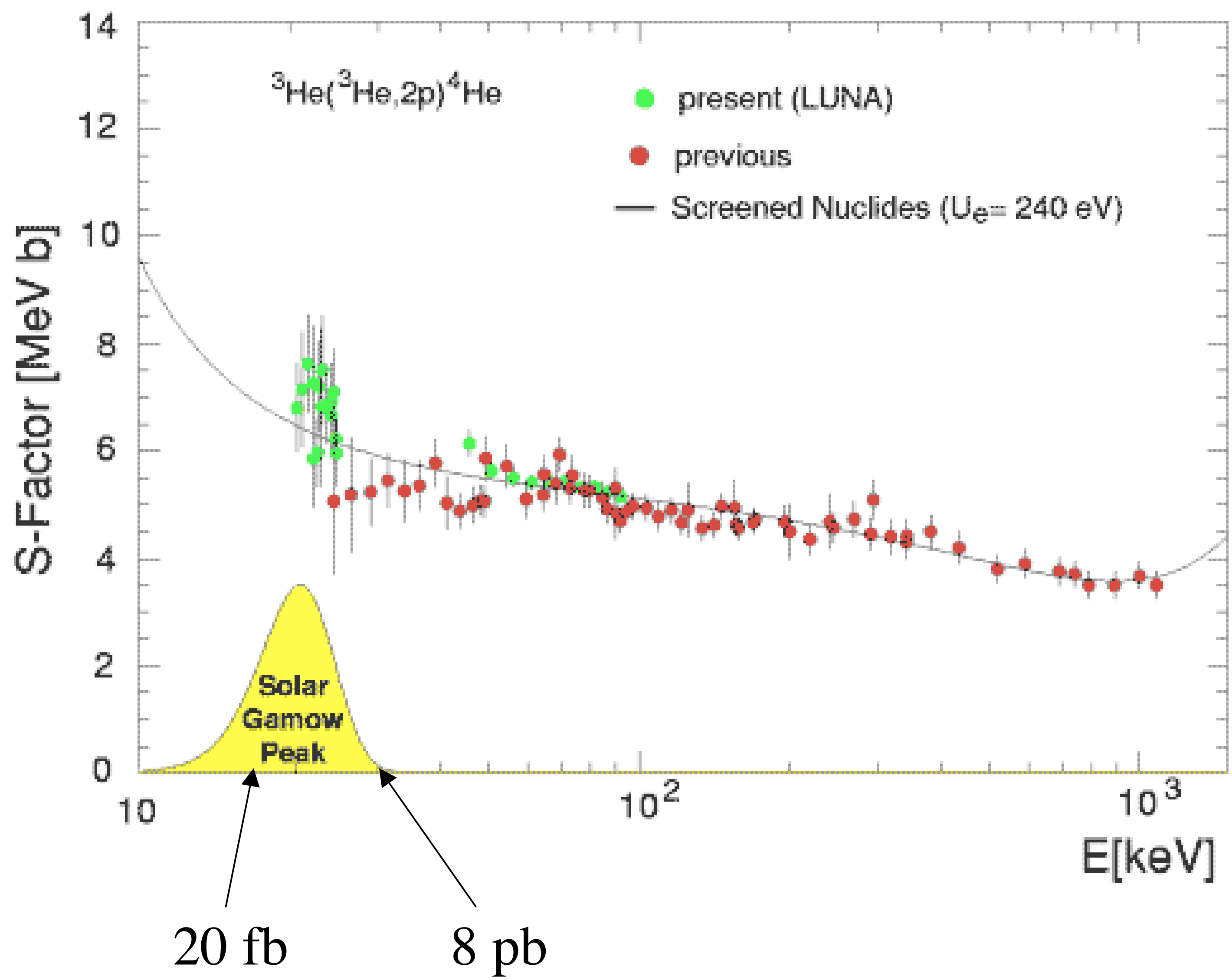
- Direct backgrounds from primary muons.
- Secondary backgrounds from spallation reactions products.



$\Phi_{\mu} = 0.7\ m^{-2}\ h^{-1}$ $\Phi_n \approx 3*10^{-6}\ cm^{-2}\ s^{-1}$

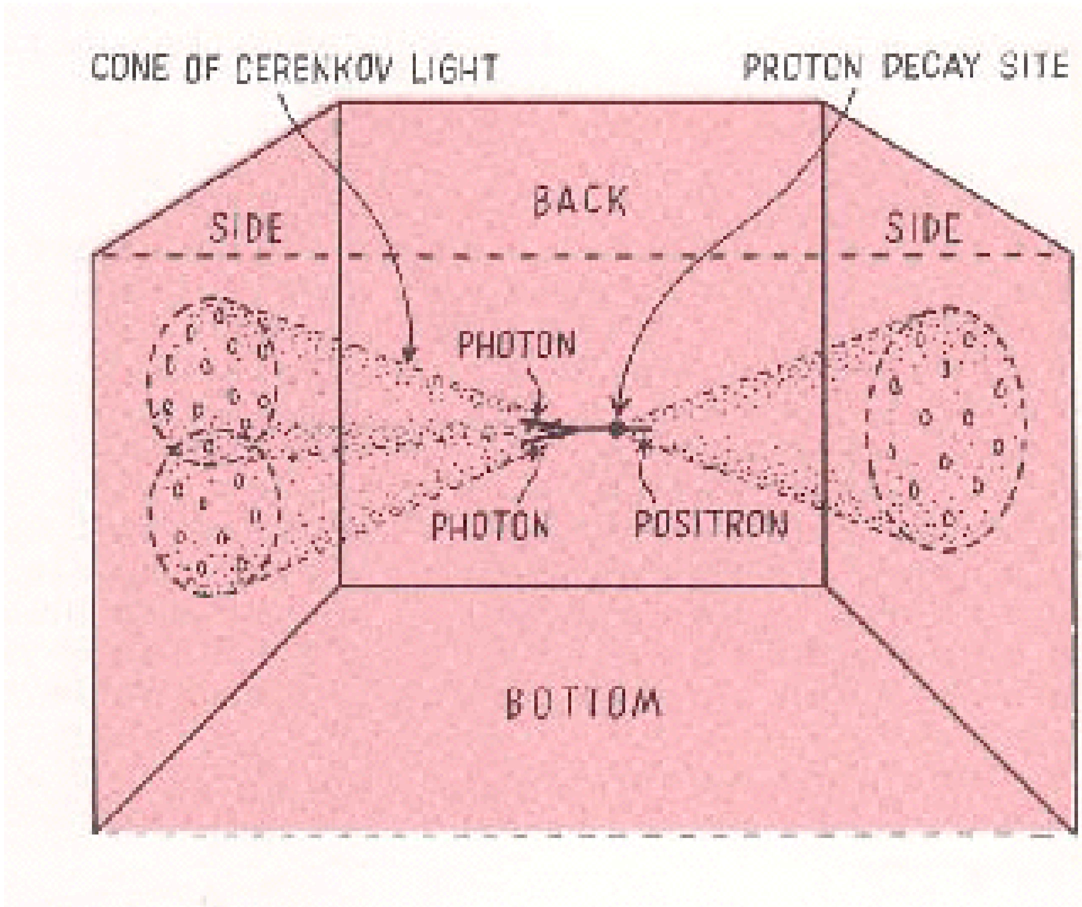


Gran Sasso Underground Laboratory



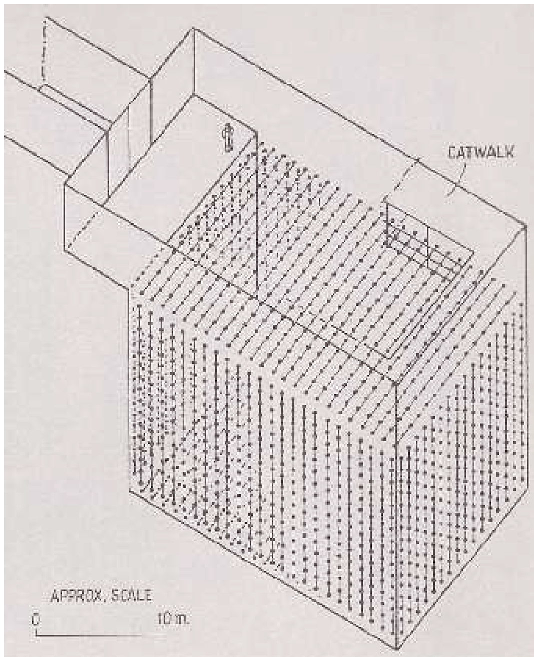
$^3He(^3He,2p)^4He$
present (LUNA)
previous
Screened Nuclides (U_e= 240 eV)
S-Factor [MeV b]
E[keV]
Solar Gamow Peak
20 fb
8 pb

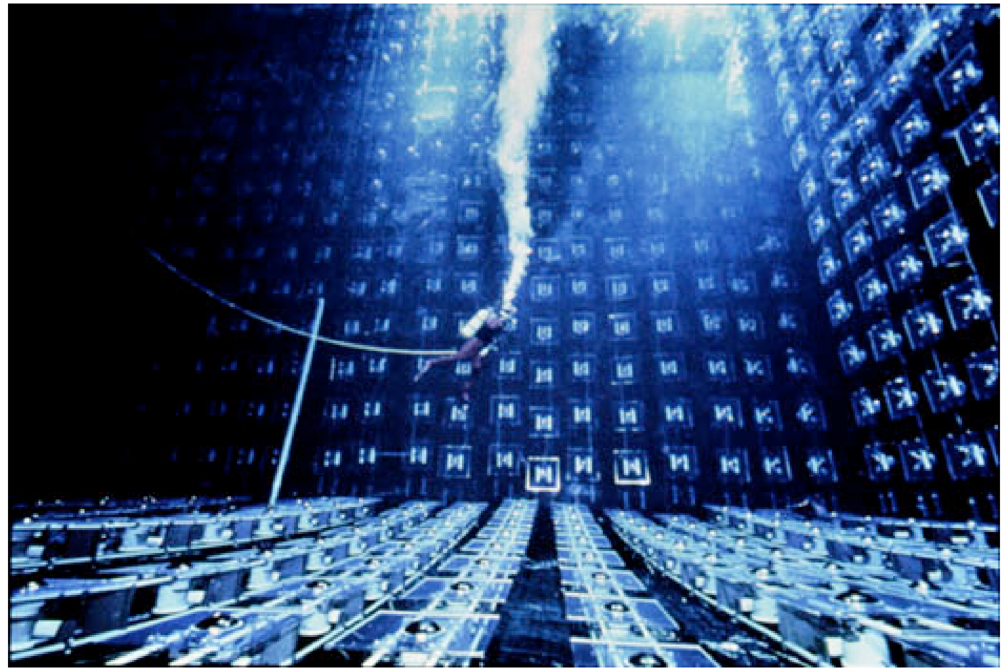
Proton Decay



$$p \rightarrow \pi^0 + e^+$$

Experimental Search for Proton Decay

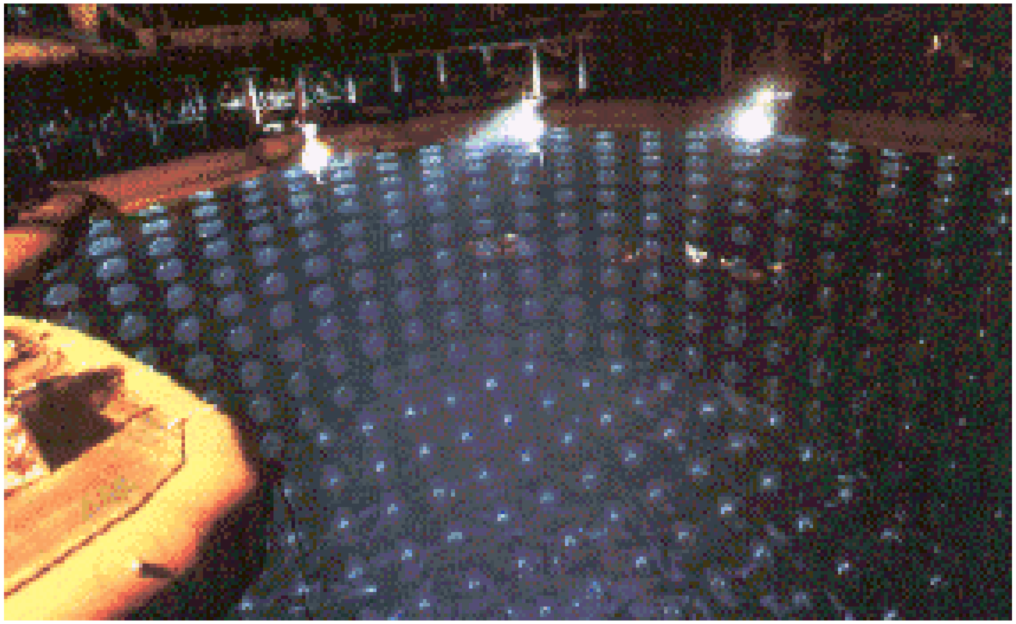


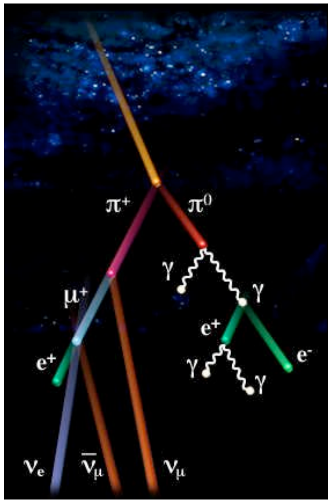


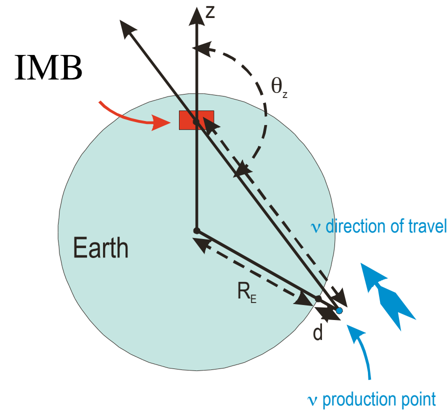
IMB

Irvine-Michigan-Brookhaven

KamiokaNDE







$$L(\vartheta_z) = \sqrt{R^2\cos^2\vartheta_z + 2Rd + d^2} - R\cos\vartheta_z$$

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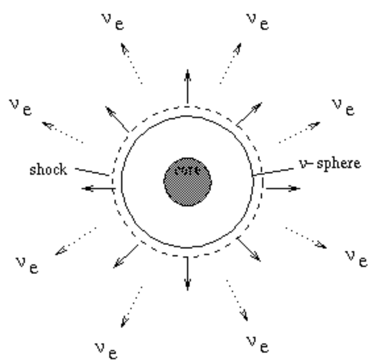
well not only globally but also in small regions. The simulation predicts that 34% ± 1% of the events should have an identified muon decay while our data has 26% ± 3%. This discrepancy could be a statistical fluctuation or a systematic error due to (i) an incorrect assumption as to the ratio of muon ν's to electron ν's in the atmospheric fluxes, (ii) an incorrect estimate of the efficiency for our observing a muon decay, or (iii) some other as-yet-unaccounted-for physics. Any effect of this discrepancy has not been considered in calculating the nucleon-decay results.

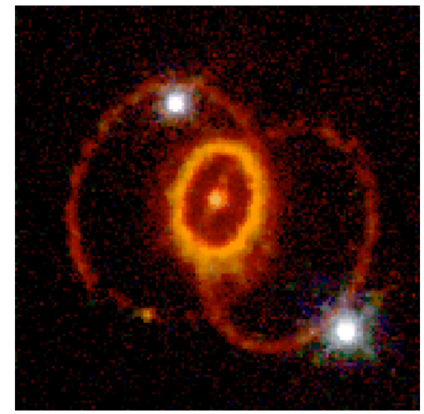
decay. Also, there is no significant excess of events observed in any decay mode that would indicate a nucleon-decay signal. The lower limits for the nucleon lifetime range from roughly order of 10^{31} years to order of 10^{32} years. We believe our background estimate is now limited by systematic uncertainties in the atmospheric ν flux and the available data for ν interactions. To reduce these systematic uncertainties will require specific experiments dedicated to a more detailed understanding of low-energy ν interactions and more precise atmospheric ν flux measurements.

IMB

“Expect the unexpected”

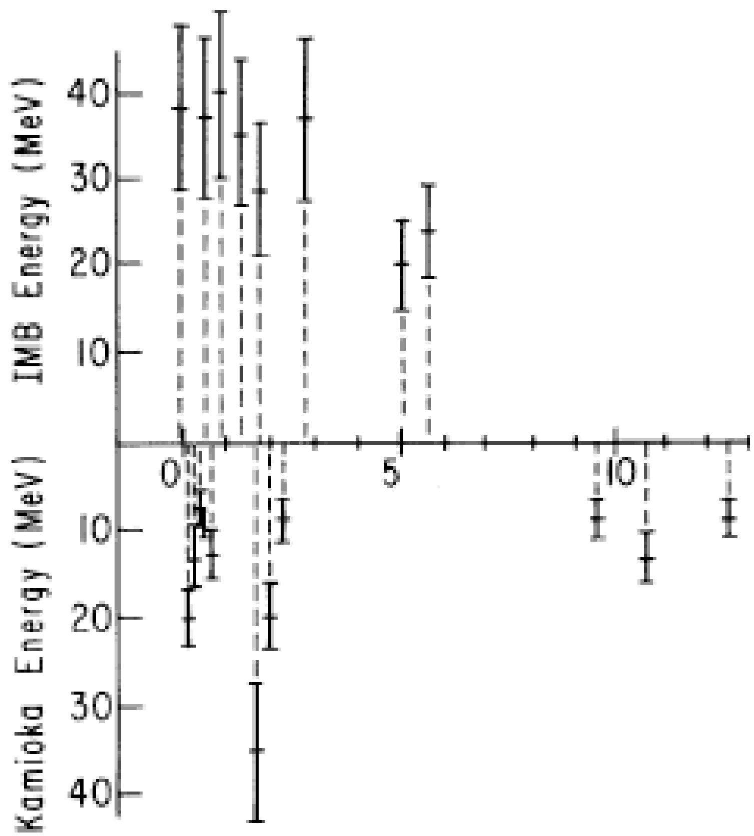
Supernova Neutrinos





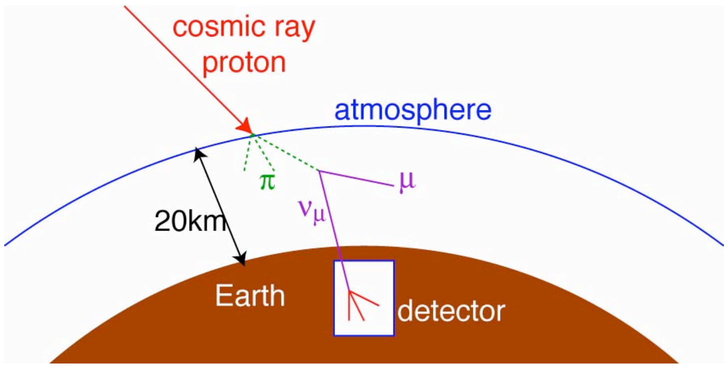
IMB energy

Kamioka energy



Time (sec)

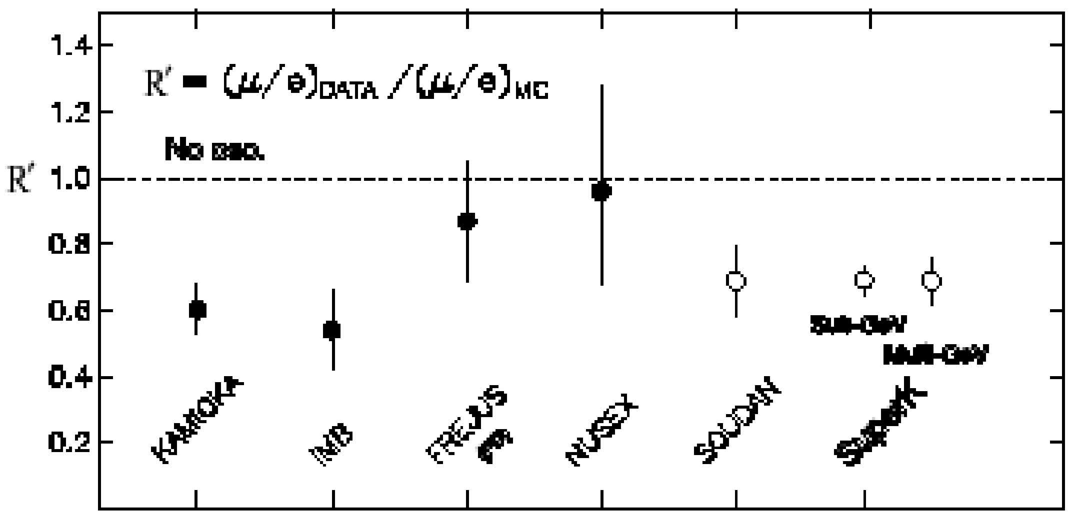
Atmospheric Neutrinos



$$\pi \rightarrow \mu + \nu_\mu$$

$$\mu \rightarrow e + \nu_e + \nu_\mu$$

$$\longrightarrow \quad N\nu_\mu = 2N\nu_e$$



Too few ν_μ

Бруно Понтекорво

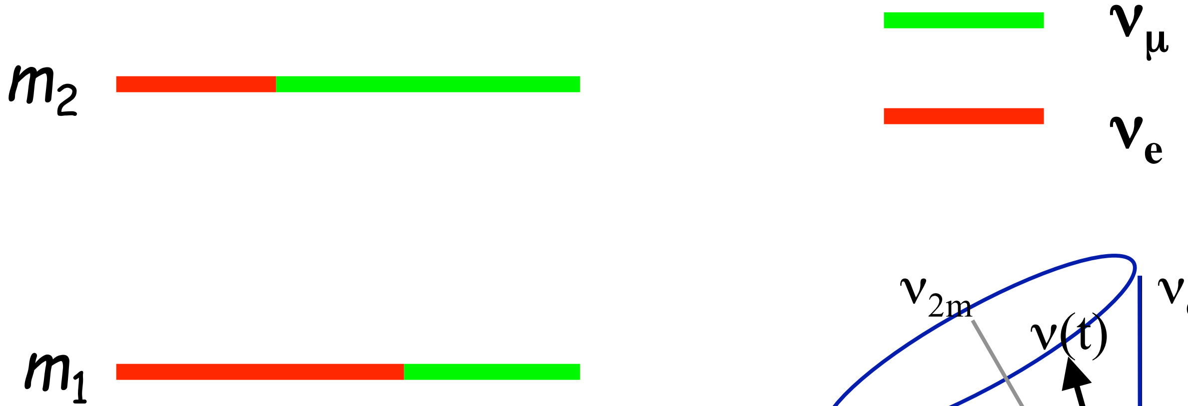
Neutrino Oscillations

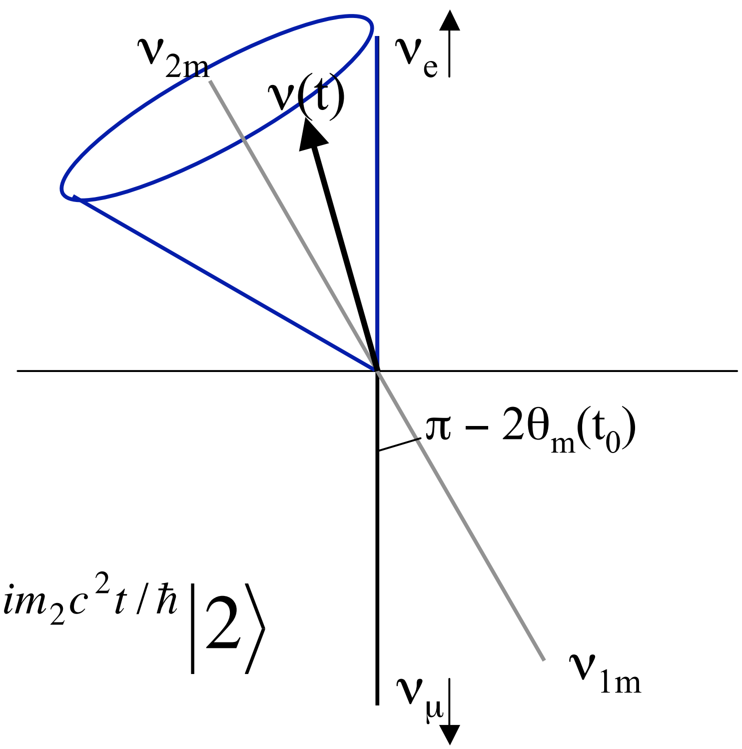
$$\left|\nu_\mu, t\right\rangle = |1\rangle \cos\theta \, e^{-im_1^2 c^3 t/2p} + |2\rangle \sin\theta \, e^{-im_2^2 c^3 t/2p}$$

$$P = \left|\left\langle \nu_\mu \middle| \nu_\mu, t \right\rangle\right|^2 = 1 - \sin^2 2\theta \sin^2\left(1.27 \frac{\Delta m^2 c^4}{\mathrm{eV}^2} \frac{\mathrm{GeV}}{c|\vec{p}|} \frac{ct}{\mathrm{km}}\right)$$

$$\Delta m^2 = m_1{}^2 - m_2{}^2$$

Neutrino Oscillations in the rest frame

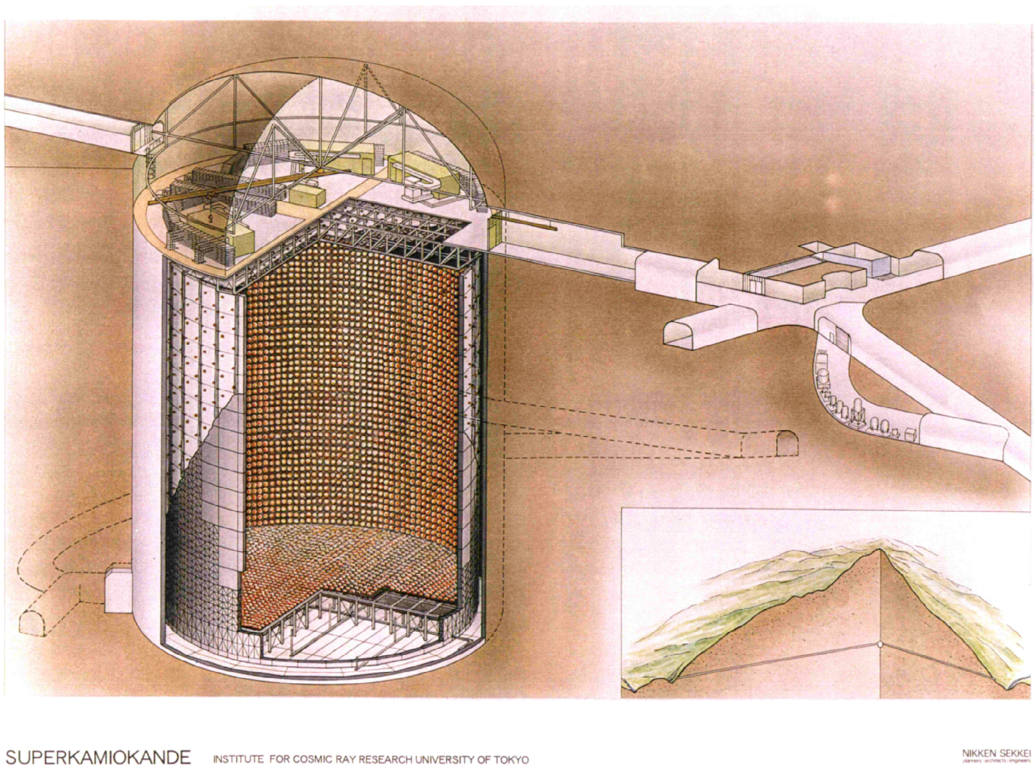


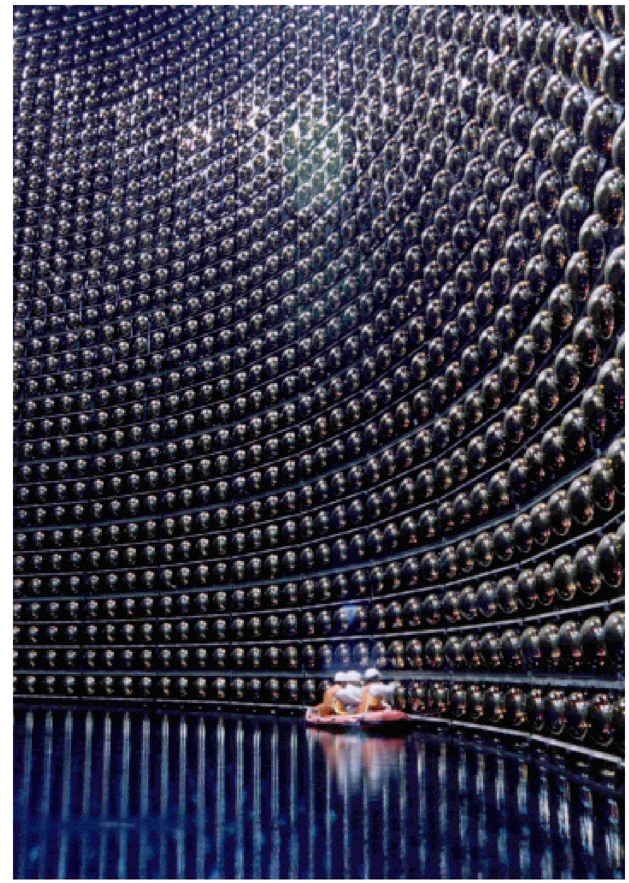


$$\left|\Psi(t)\right\rangle = \cos\theta e^{-im_1c^2t/\hbar}\left|1\right\rangle + \sin\theta e^{-im_2c^2t/\hbar}\left|2\right\rangle$$

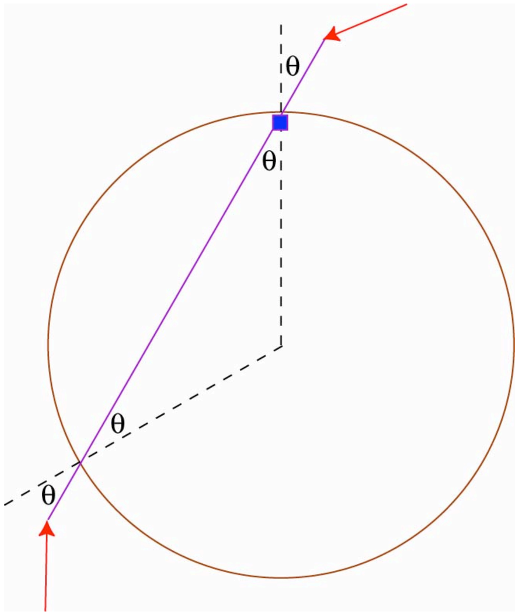
$$P_{\mu\mu}(t) = \left|\left\langle\Psi(0)\middle|\Psi(t)\right\rangle\right|^2 = 1 - 2\sin^2(2\theta)\sin^2\left[\left(\frac{m_1c^2 - m_2c^2}{2\hbar}\right)t\right]$$

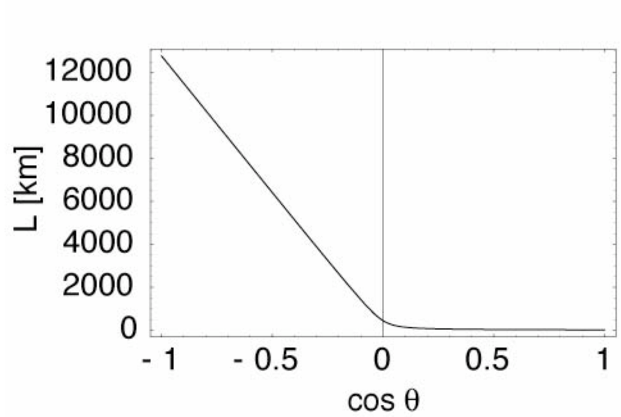
SuperKamiokande

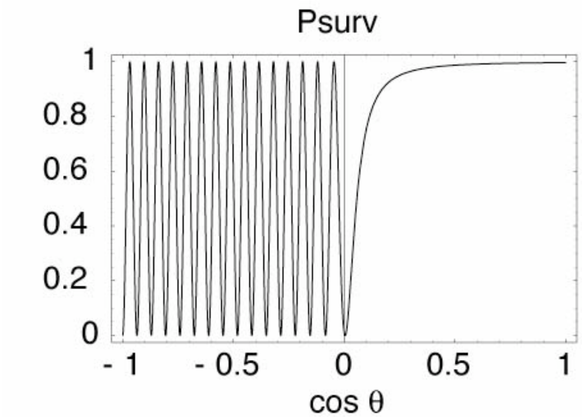


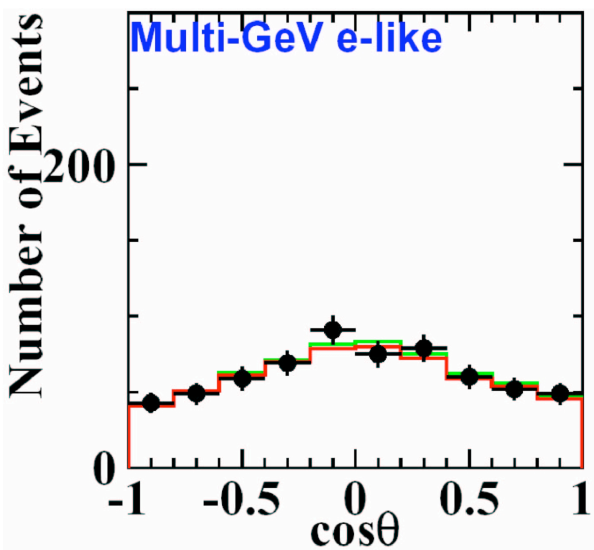


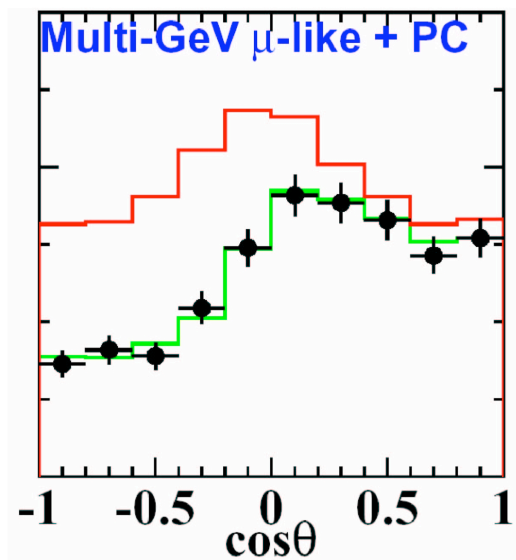
Atmospheric neutrinos as a source for oscillation experiments



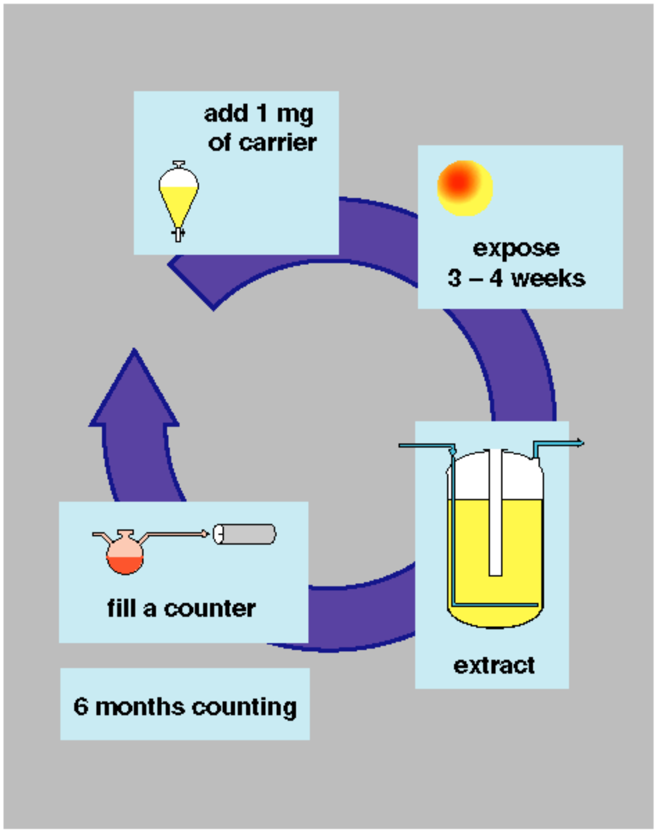


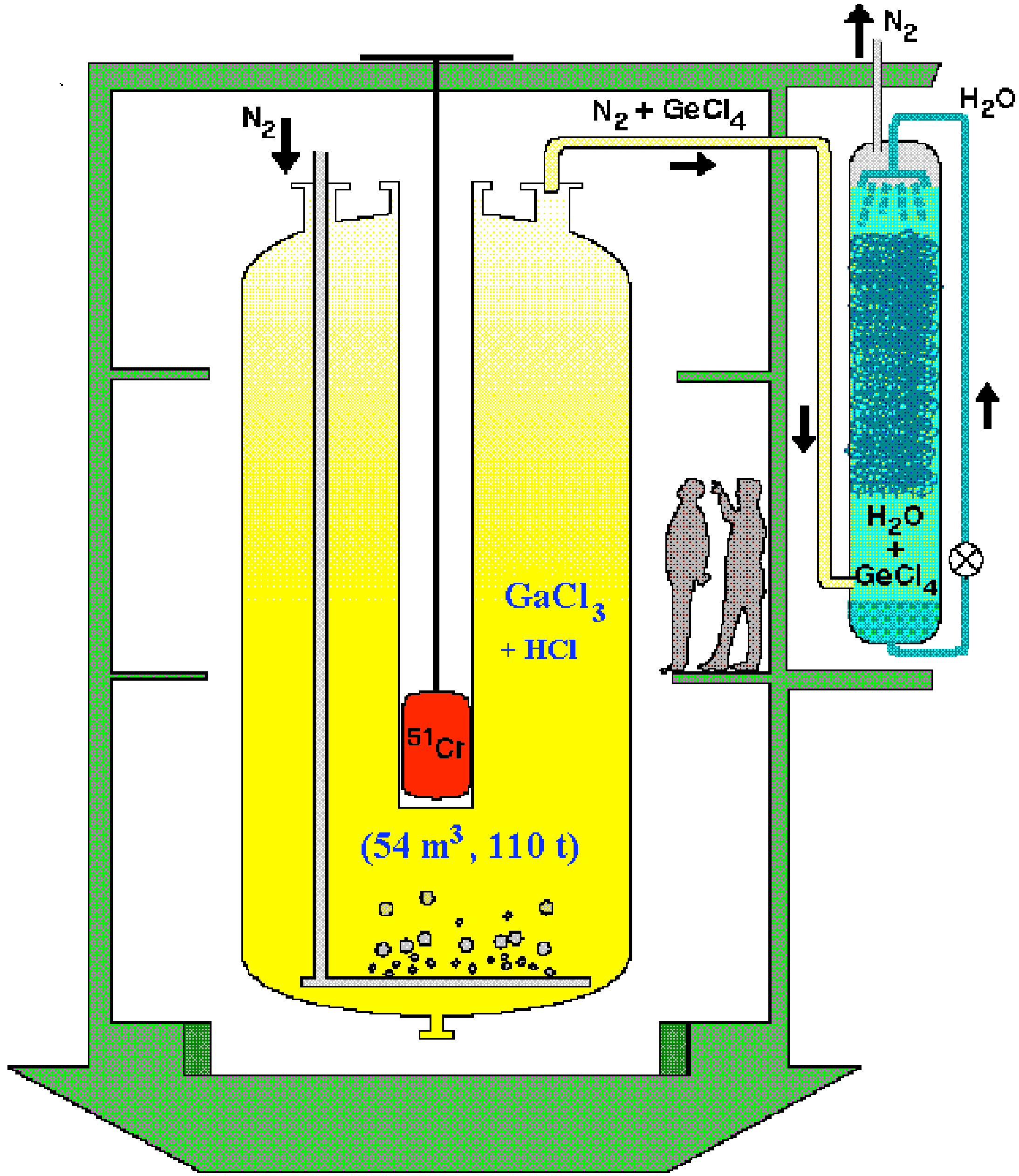




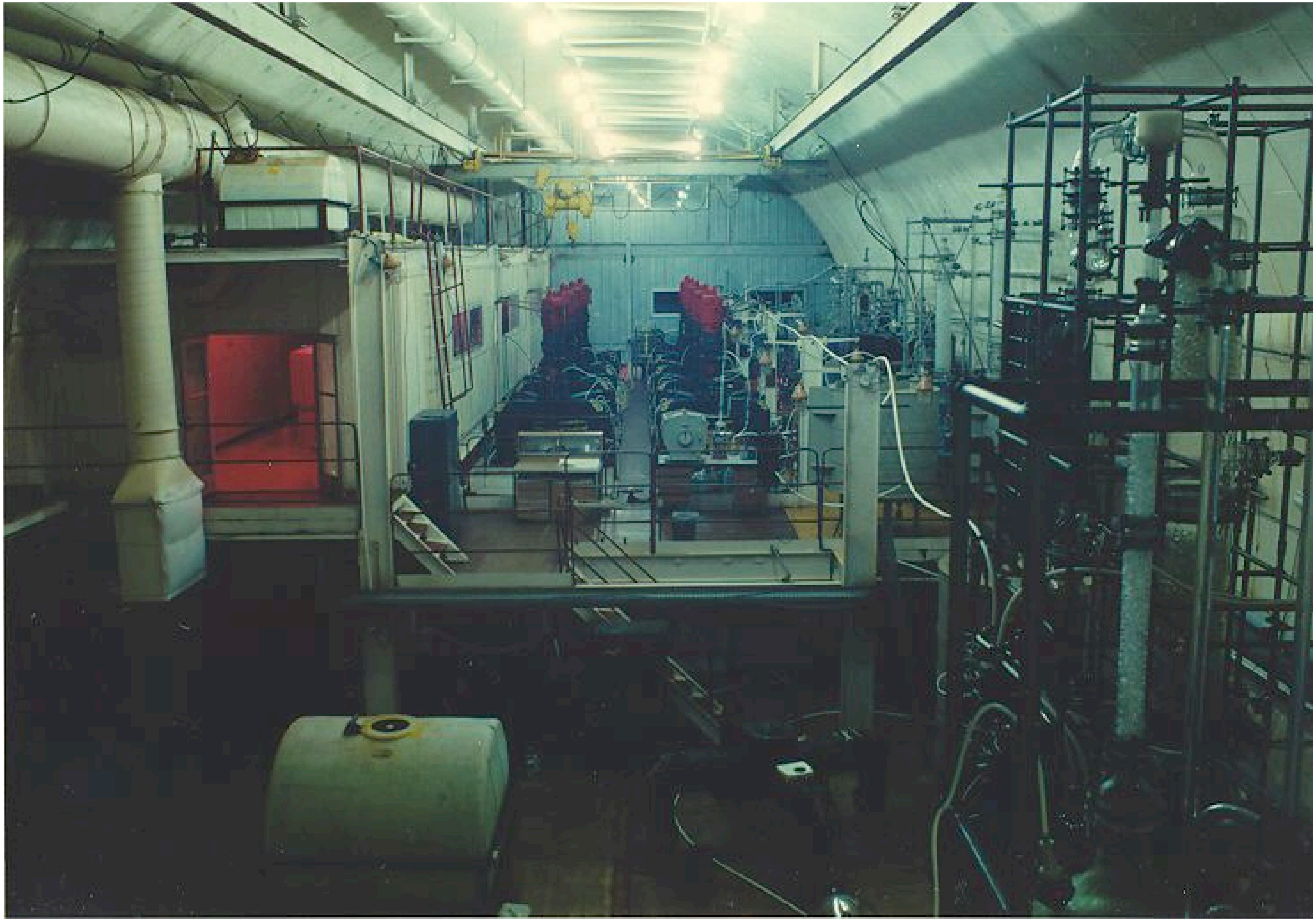


Evidence for neutrino oscillations from SuperK



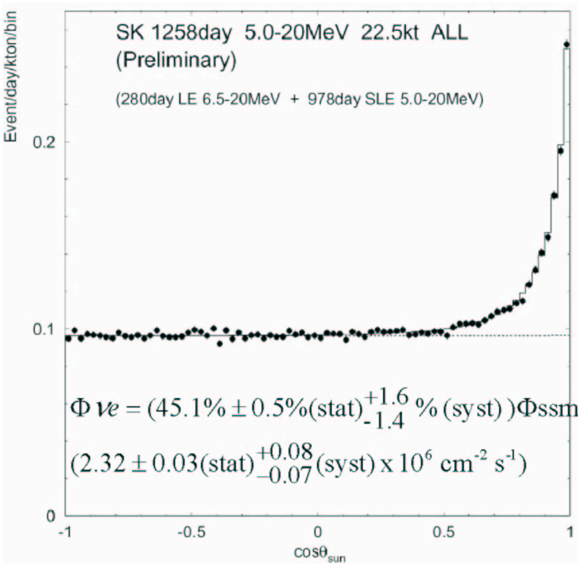


Gallium Experiment-Gallium Neutrino Observatory

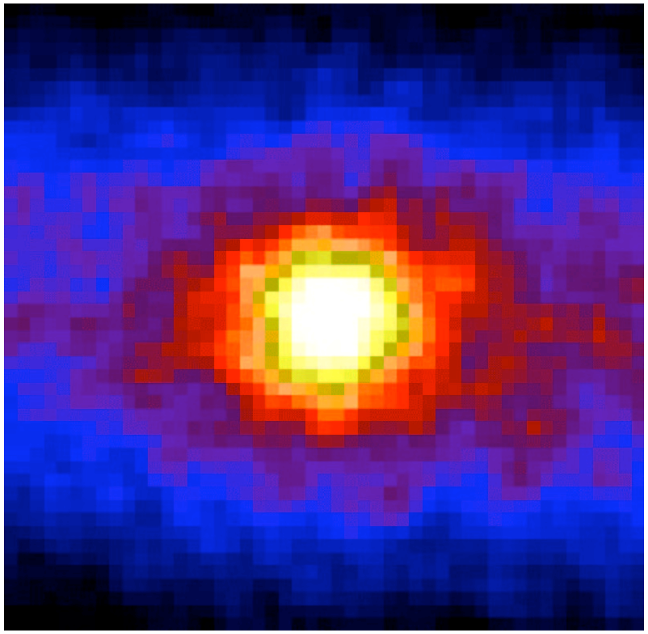


Soviet American Gallium Experiment

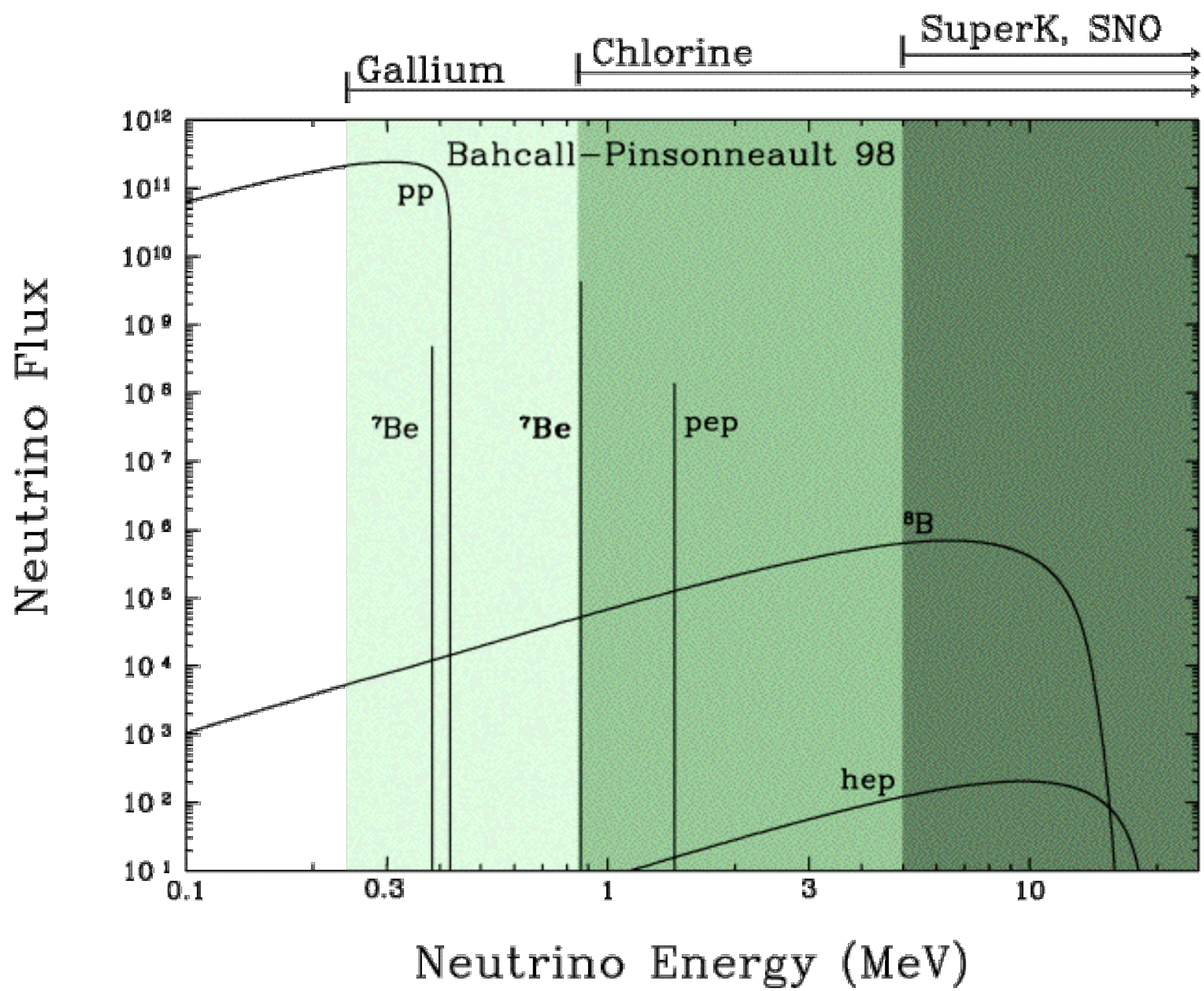
Solar Neutrinos



SuperK



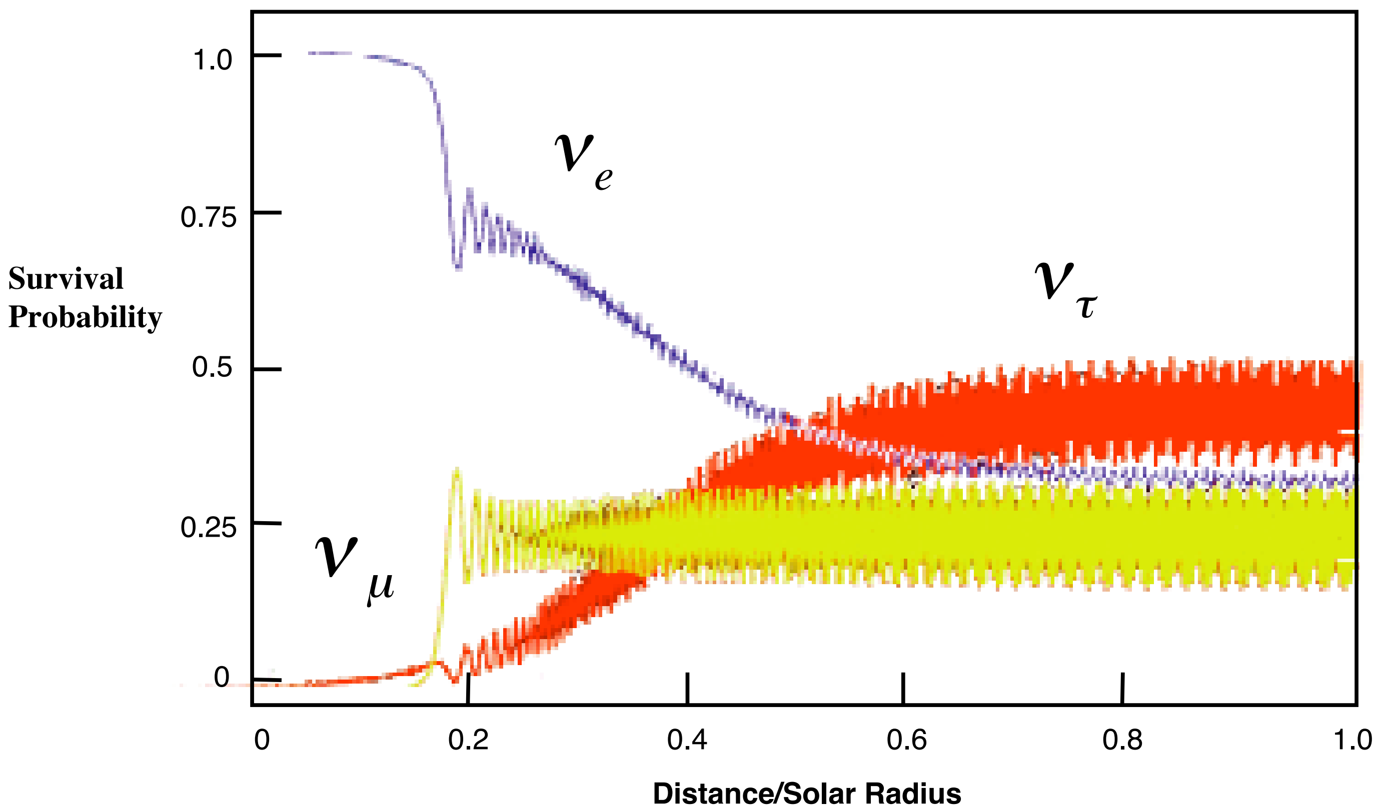
The Sun as seen from underground



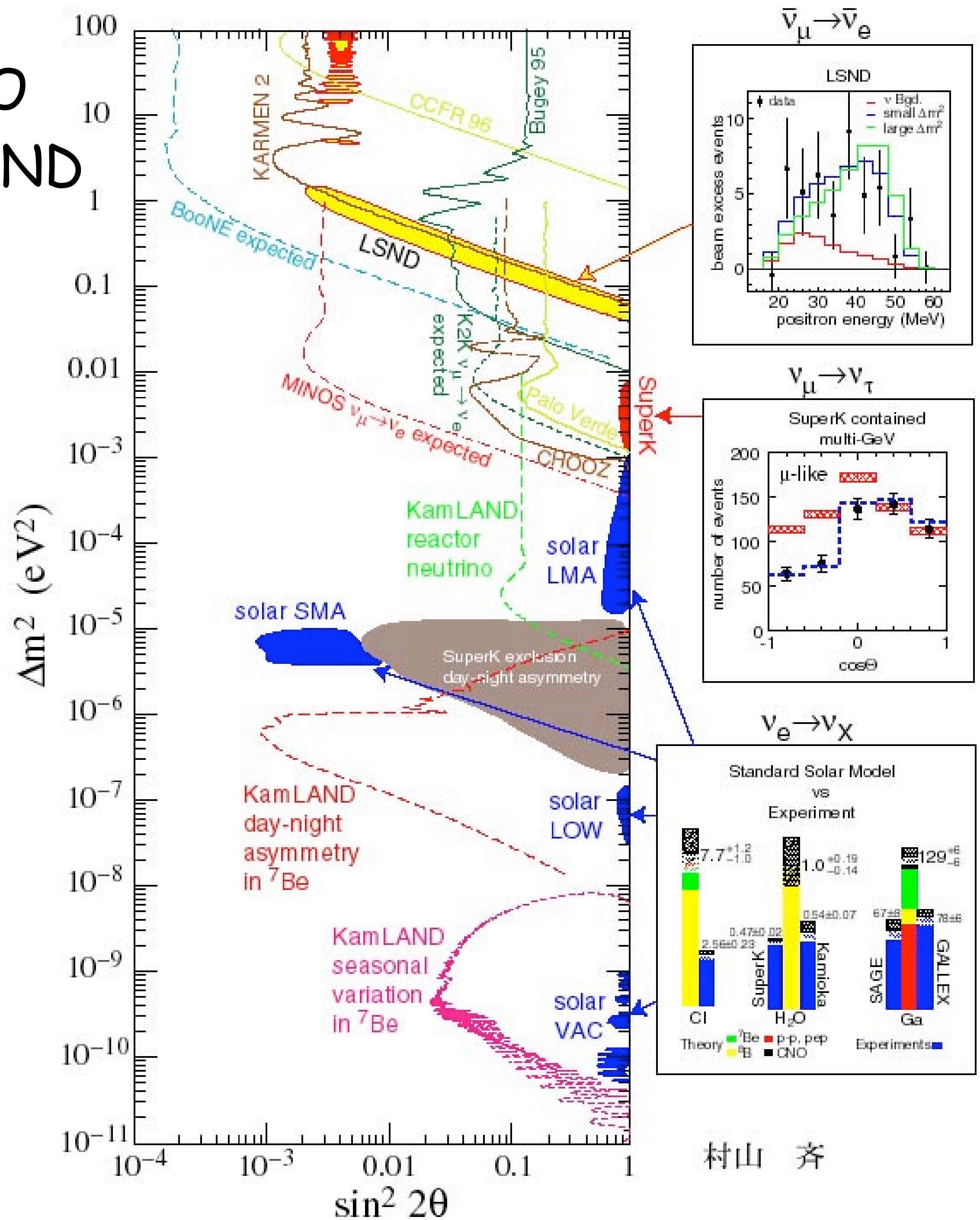
SuperK, SNO
Chlorine
Gallium
Bahcall−Pinsonneault 98
pp
7Be
7Be
pep
8B
hep
Neutrino Flux
Neutrino Energy (MeV)
10^12
10^11
10^10
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
0.1
0.3
1
3
10

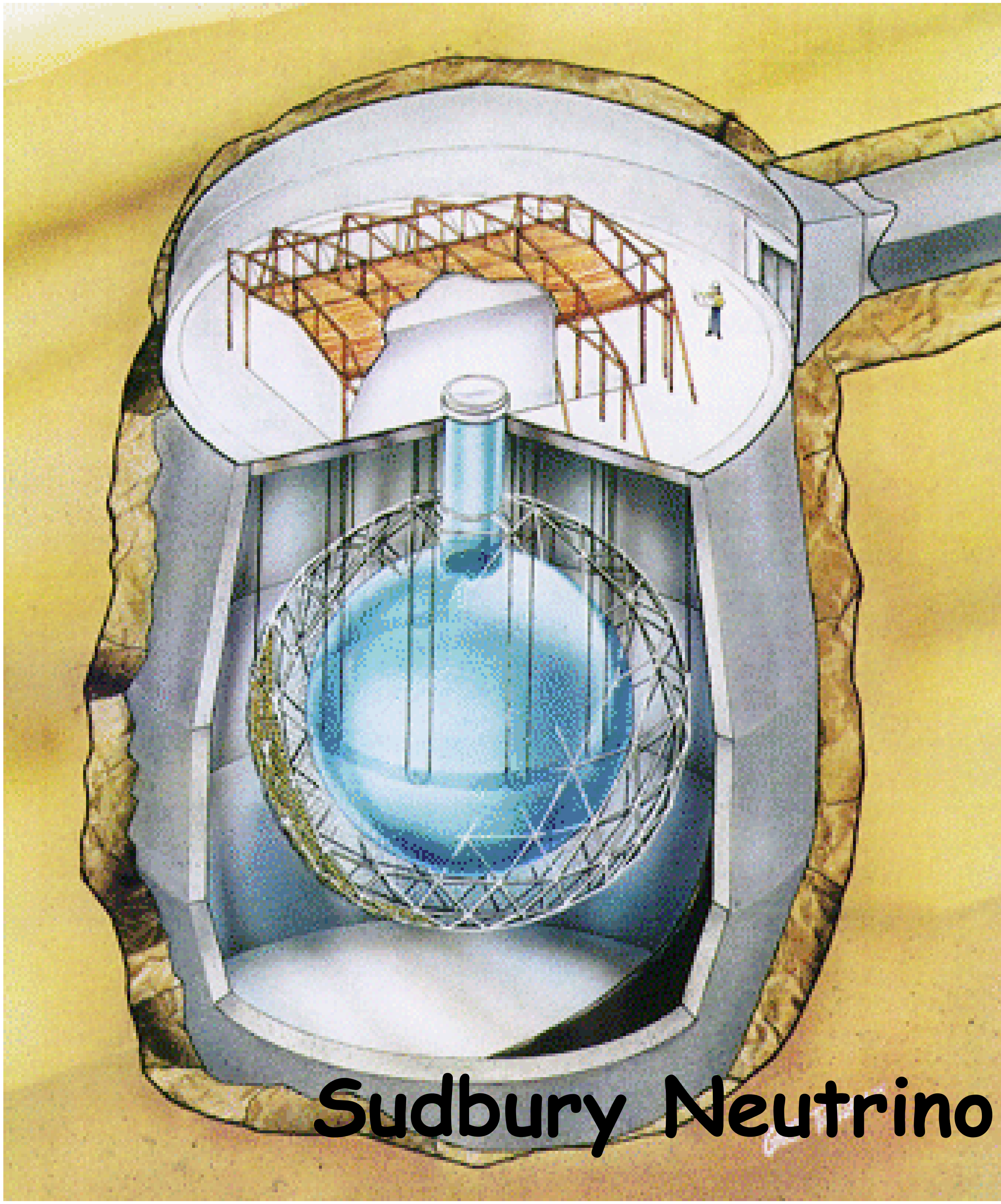
MSW Effect

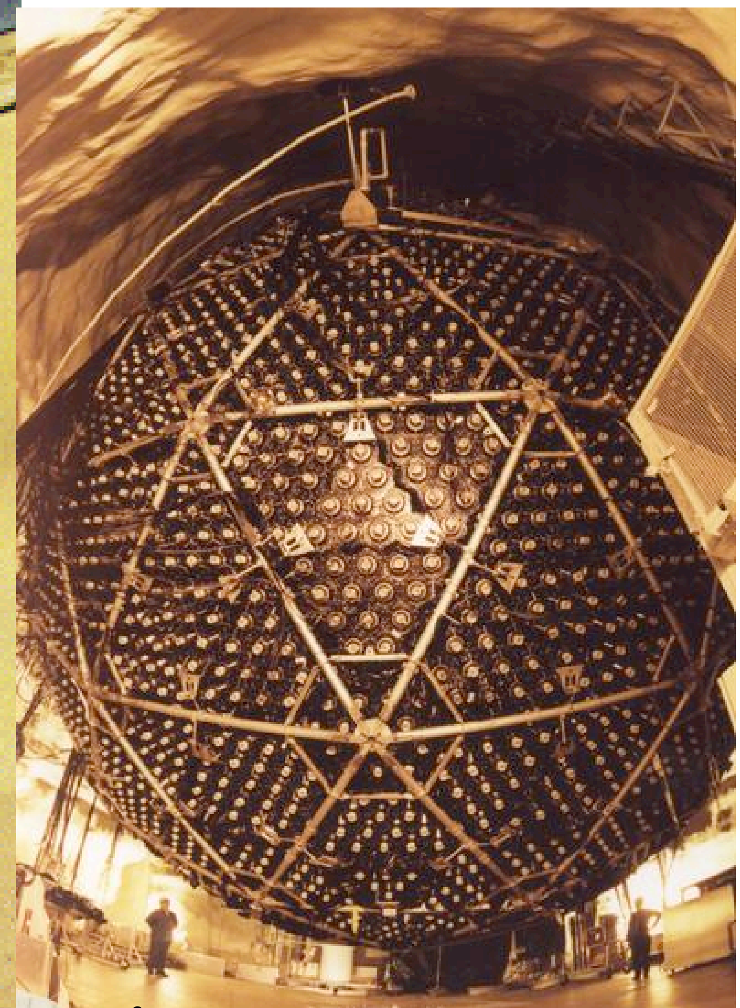
ν_e NC and CC ν_τ ν_μ NC only



Before SNO And KamLAND

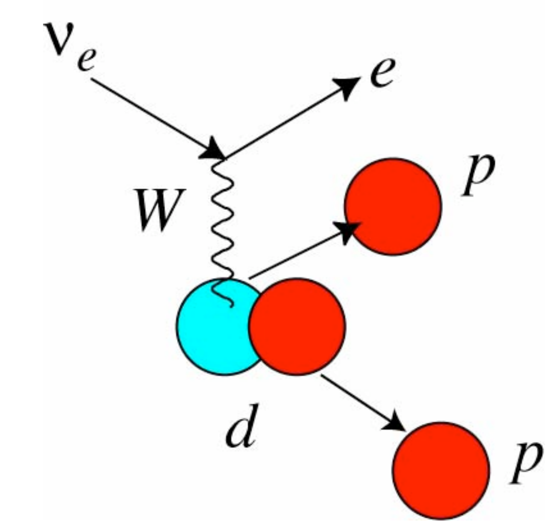




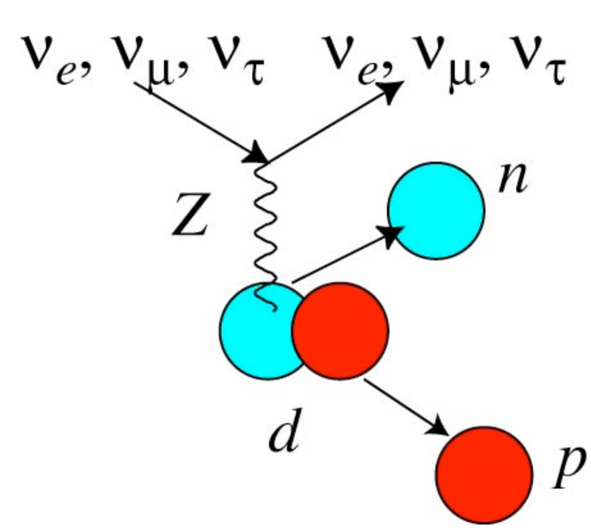


Sudbury Neutrino Observatory

Why does SNO use $300M worth of heavy water?



Charged Current

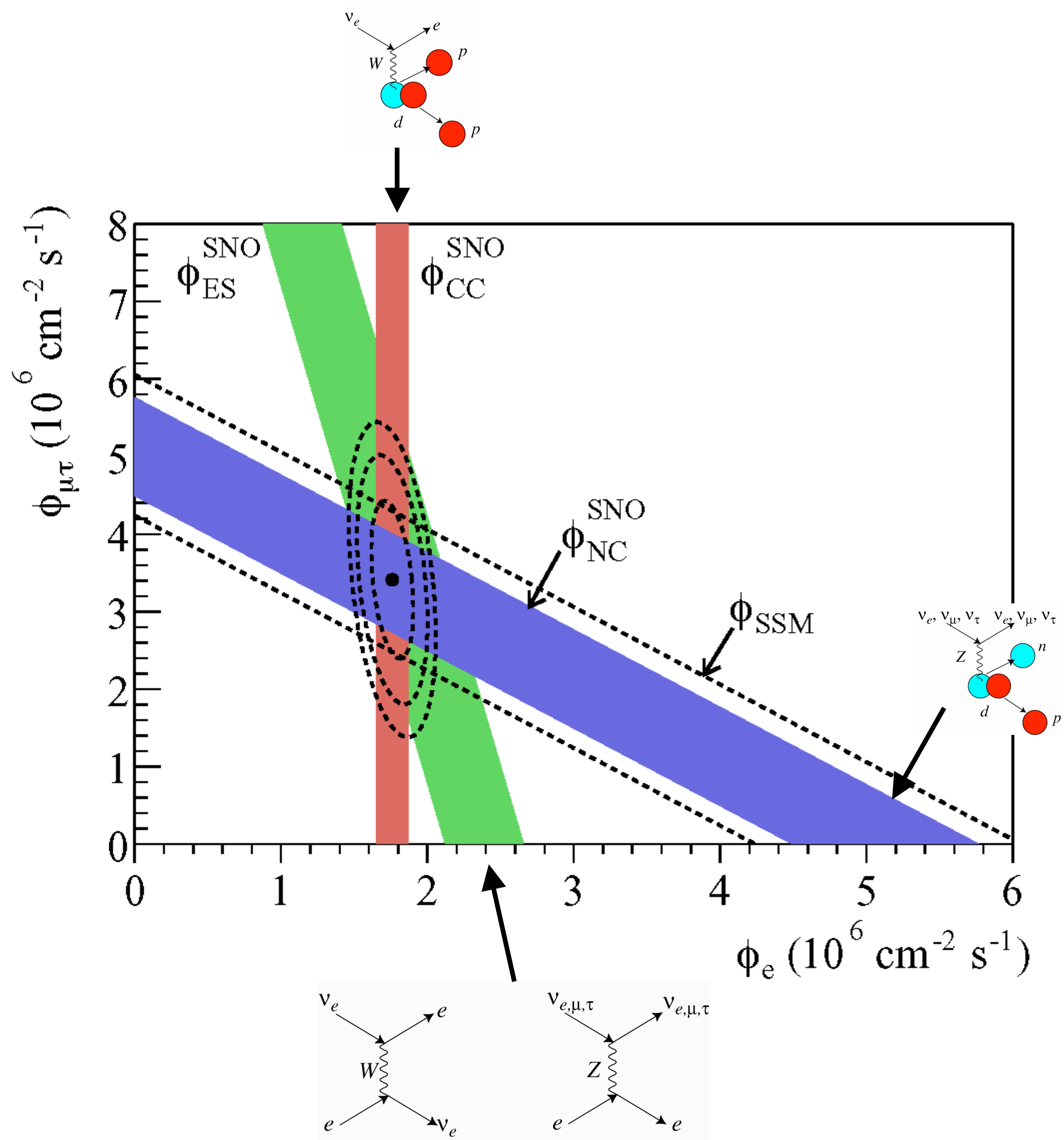


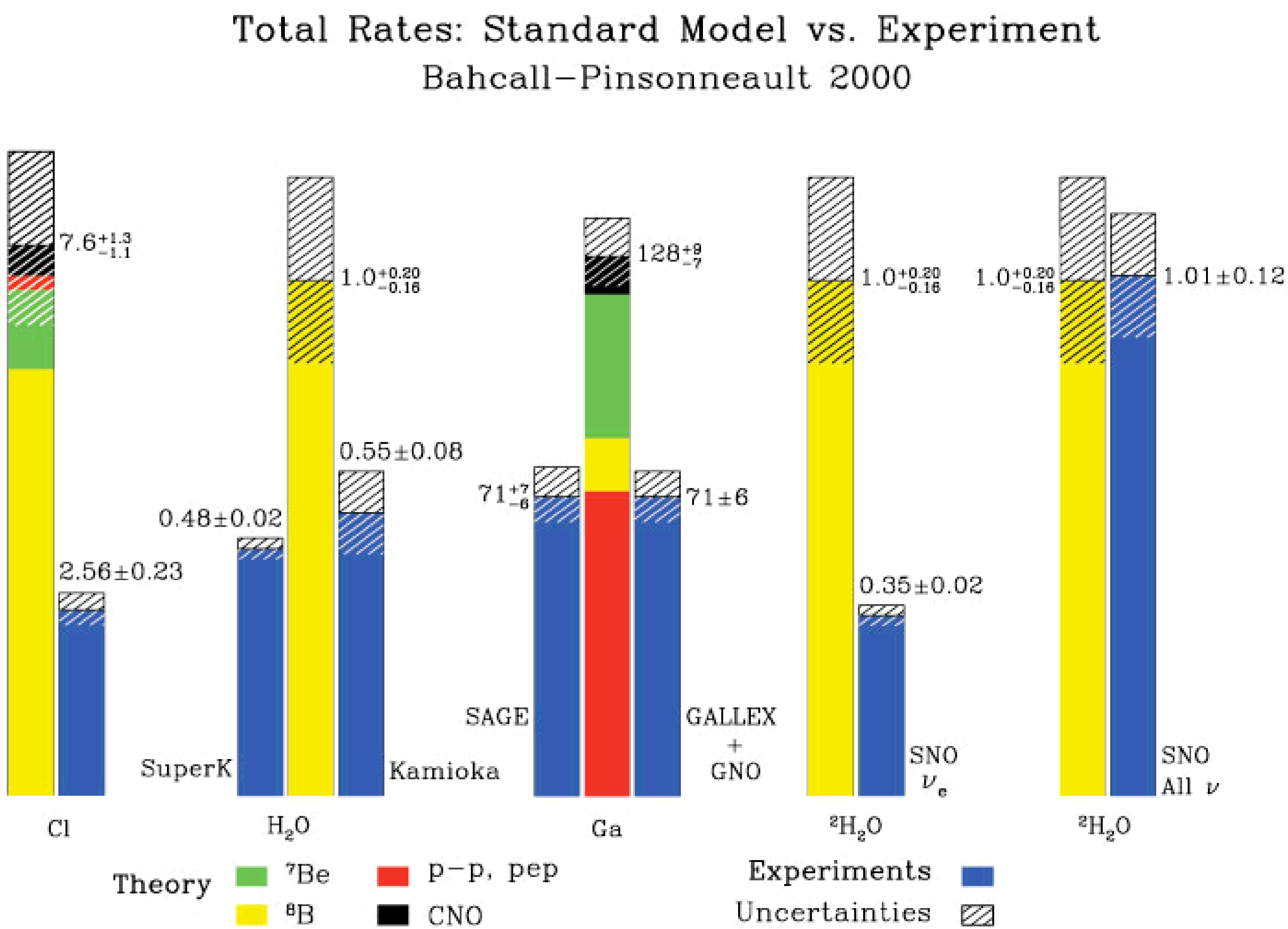
Neutral Current

Fluxes

(10^6 cm^{-2} s^{-1})

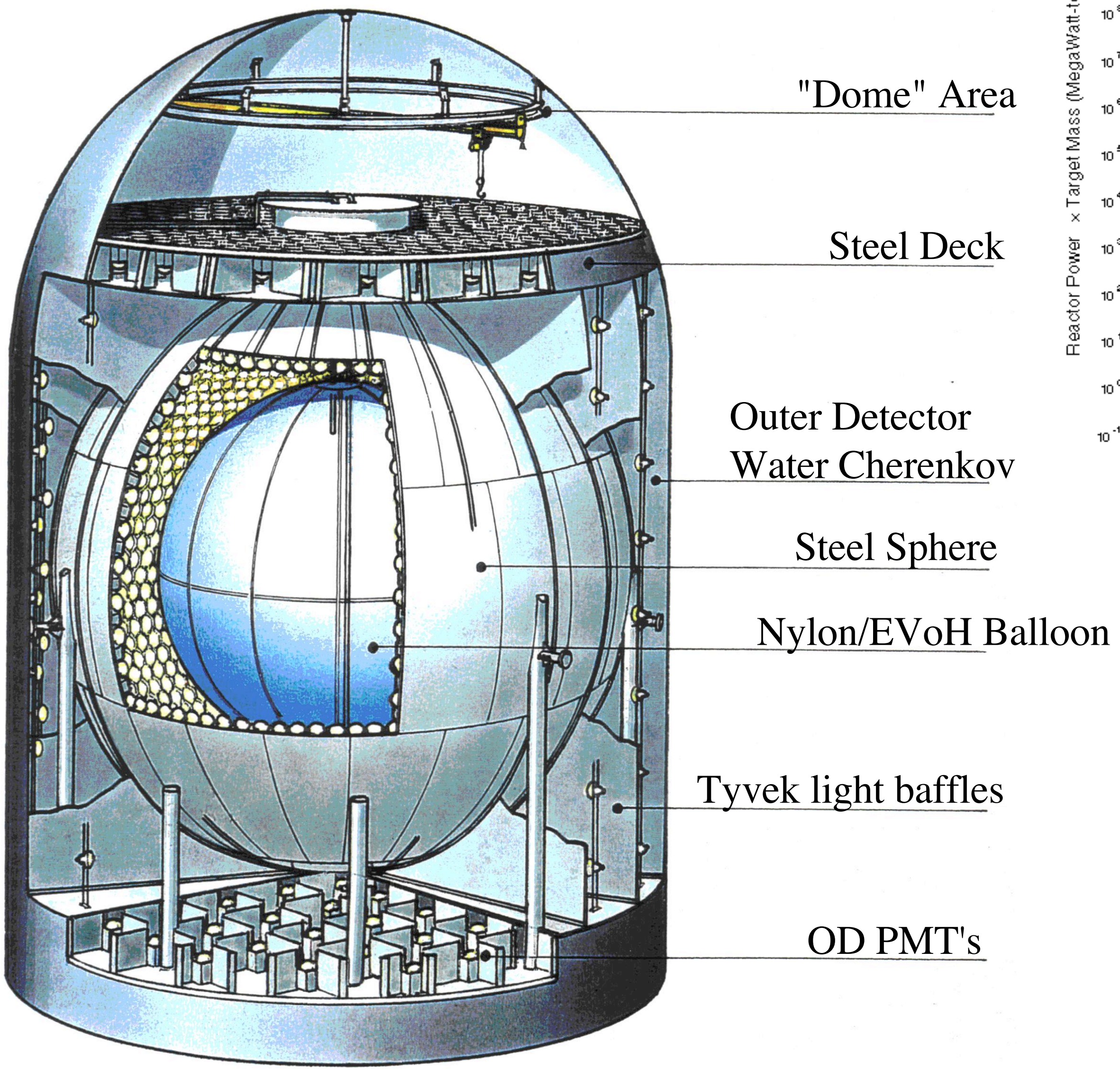
ν_e:	1.76(11)
$\nu_{\mu\tau}$:	3.41(66)
ν_{total}:	5.09(64)
ν_{SSM}:	5.05



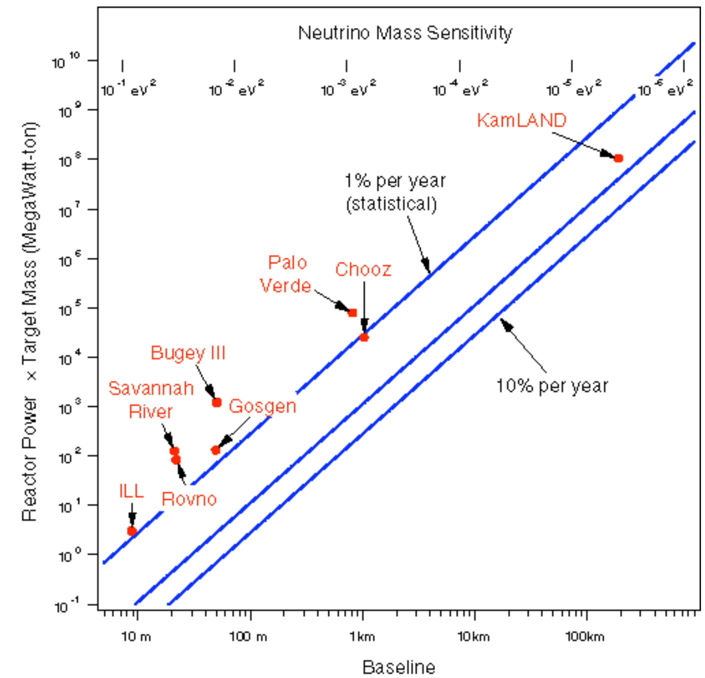


Total Rates: Standard Model vs. Experiment
Bahcall–Pinsonneault 2000
7.6$^{+1.3}_{-1.1}$
2.56±0.23
1.0$^{+0.20}_{-0.16}$
0.55±0.08
0.48±0.02
SuperK
Kamioka
128$^{+9}_{-7}$
71$^{+7}_{-6}$
71±6
SAGE
GALLEX
+
GNO
1.0$^{+0.20}_{-0.16}$
0.35±0.02
SNO
ν_e
1.0$^{+0.20}_{-0.16}$
1.01±0.12
SNO
All ν
Cl
H_2O
Ga
^2H_2O
^2H_2O
Theory
^{7}Be
^{8}B
p–p, pep
CNO
Experiments
Uncertainties

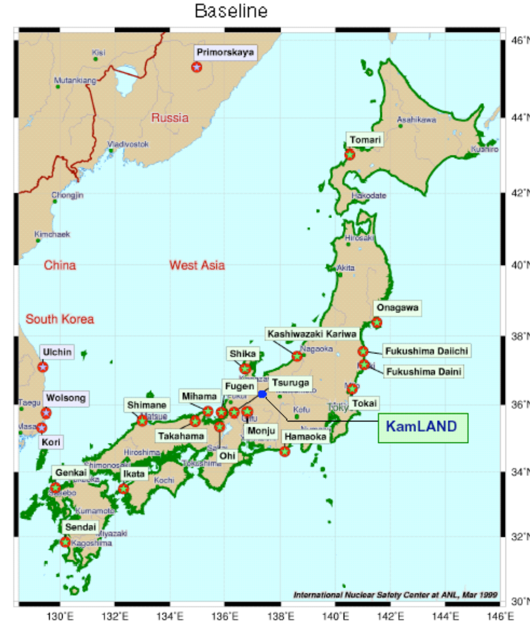
KamLAND



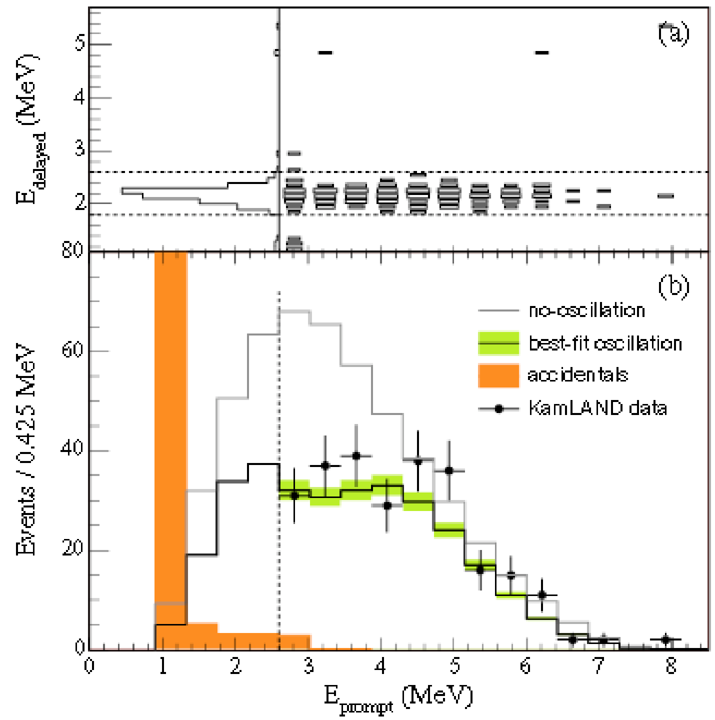
"Dome" Area
Steel Deck
Outer Detector
Water Cherenkov
Steel Sphere
Nylon/EVoH Balloon
Tyvek light baffles
OD PMT's



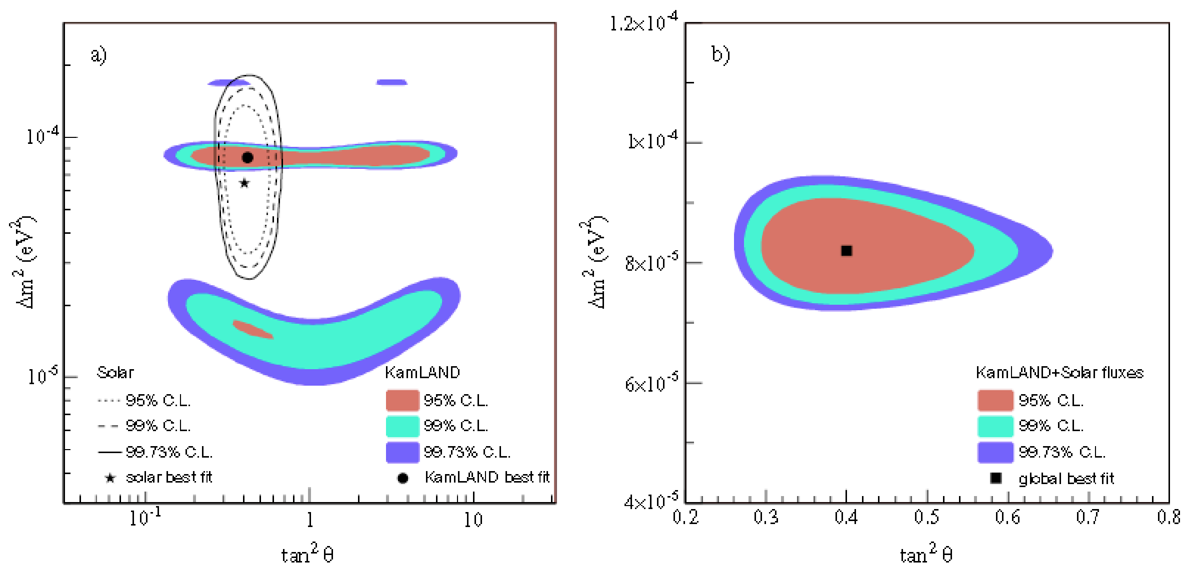
Neutrino Mass Sensitivity
10^{-1} eV^2
10^{-2} eV^2
10^{-3} eV^2
10^{-4} eV^2
10^{-5} eV^2
10^{-6} eV^2
KamLAND
1% per year
(statistical)
Palo
Verde
Chooz
Bugey III
Savannah
River
Gosgen
ILL
Rovno
10% per year
Reactor Power × Target Mass (MegaWatt-ton)
Baseline
10 m
100 m
1km
10km
100km



Primorskaya
Russia
China
West Asia
South Korea
Tomari
Onagawa
Kashiwazaki Kariwa
Fukushima Daiichi
Fukushima Daini
Shika
Tsuruga
Fugen
Tokai
Mihama
Shimane
Takahama
Monju
Hamaoka
Ohi
Ikata
Genkai
Sendai
Ulchin
Wolsong
Kori
KamLAND
International Nuclear Safety Center at ANL, Mar 1999

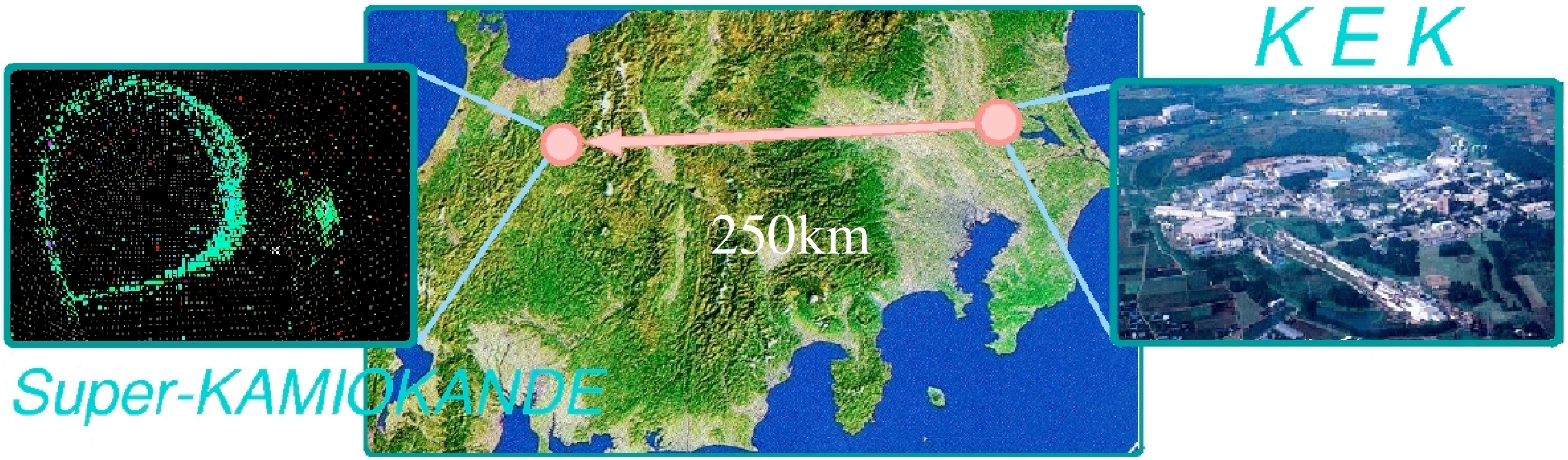


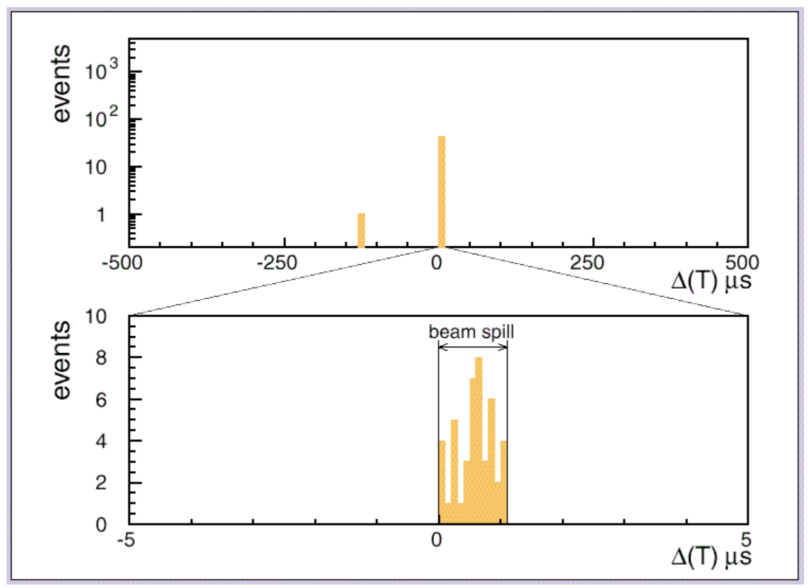
(a)
(b)
$E_{delayed}$ (MeV)
Events / 0.425 MeV
no-oscillation
best-fit oscillation
accidentals
KamLAND data
E_{prompt} (MeV)



a)
b)
Δm^2 (eV^2)
$\tan^2\theta$
Solar
95% C.L.
99% C.L.
99.73% C.L.
solar best fit
KamLAND
95% C.L.
99% C.L.
99.73% C.L.
KamLAND best fit
KamLAND+Solar fluxes
95% C.L.
99% C.L.
99.73% C.L.
global best fit

Long Baseline Experiments





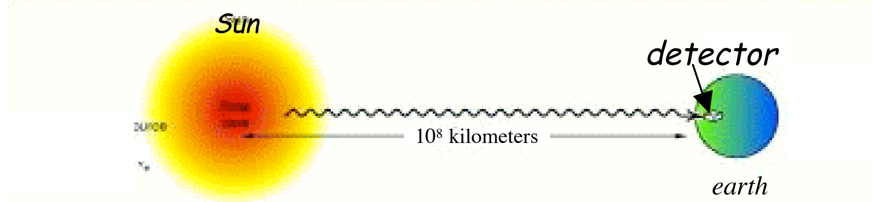
81±8 events no oscillation
56 events observed

Experimental Support

Natural Sources

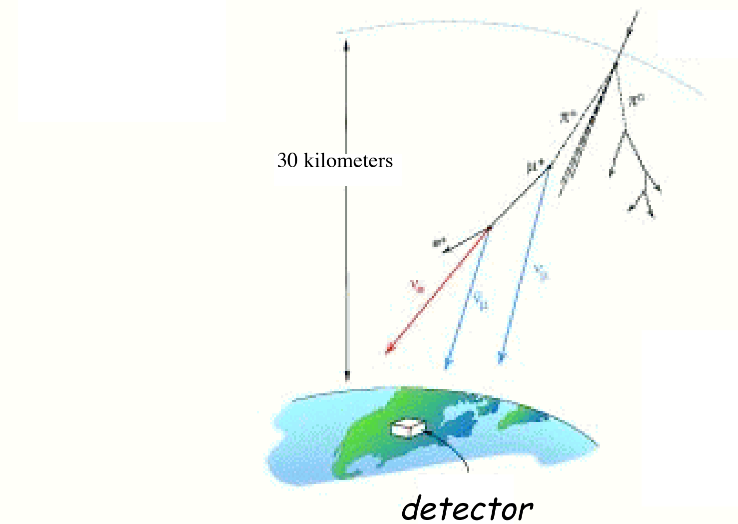
The Sun

^{37}Cl	Kamiokande
GALLEX	SuperKamiokande
SAGE	SNO



Atmospheric Neutrinos

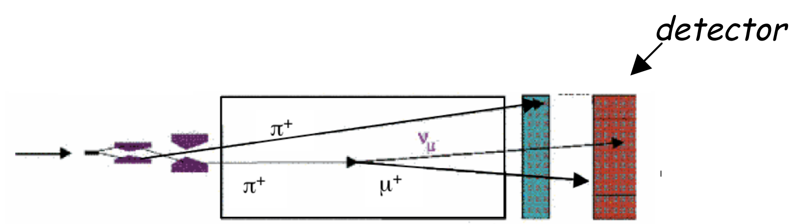
IMB	Kamiokande
Soudan	SuperKamiokande
MACRO	…



Man-Made Sources

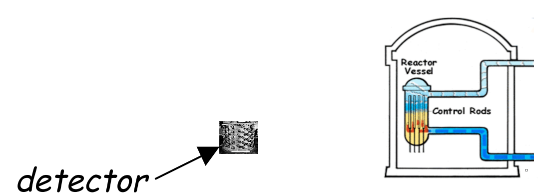
Accelerators

K2K	Chorus
Opera	(LSND)
…	

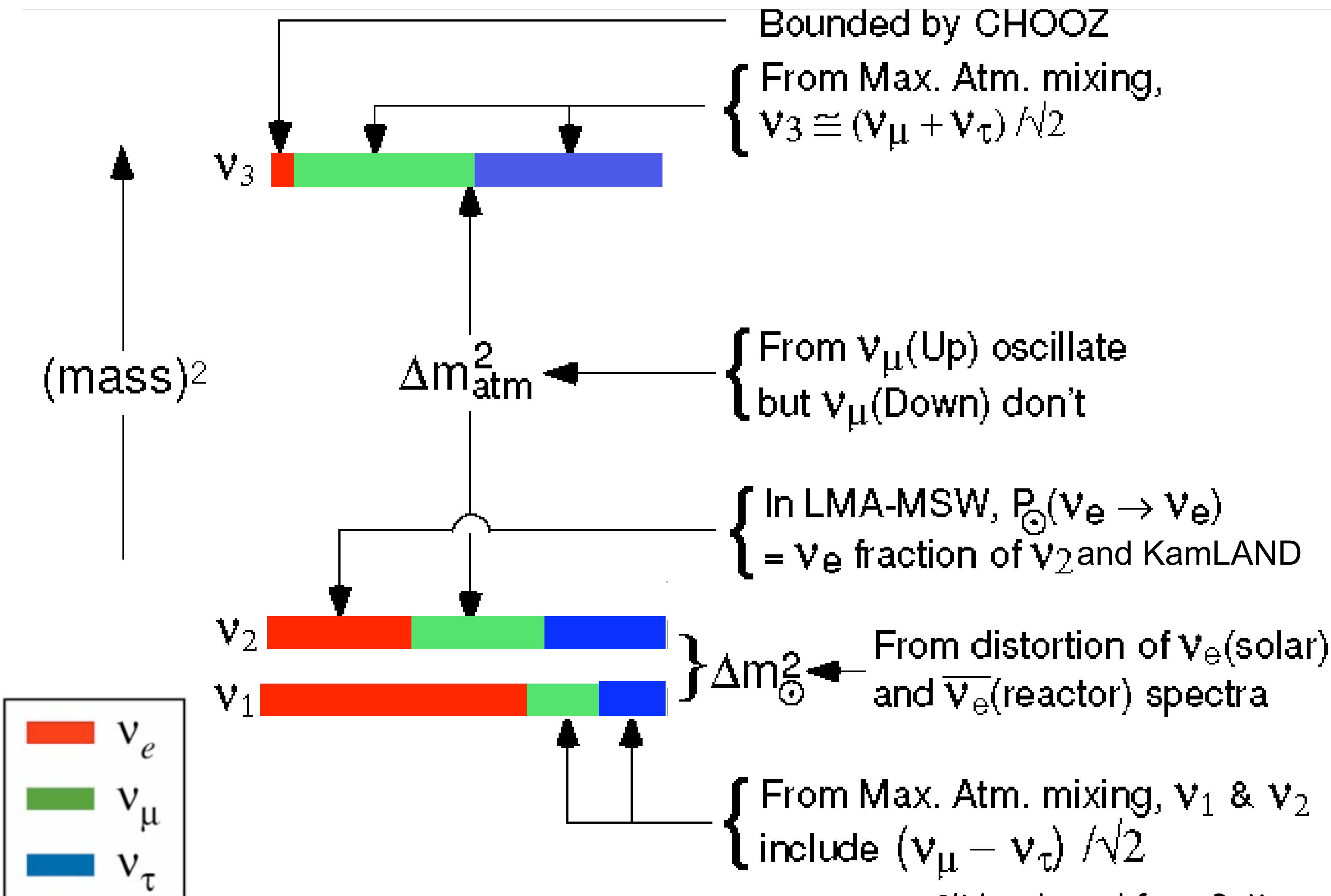


Nuclear Reactors

Bugey	Goesgen
ILL	Chooz
Palo Verde	KamLAND

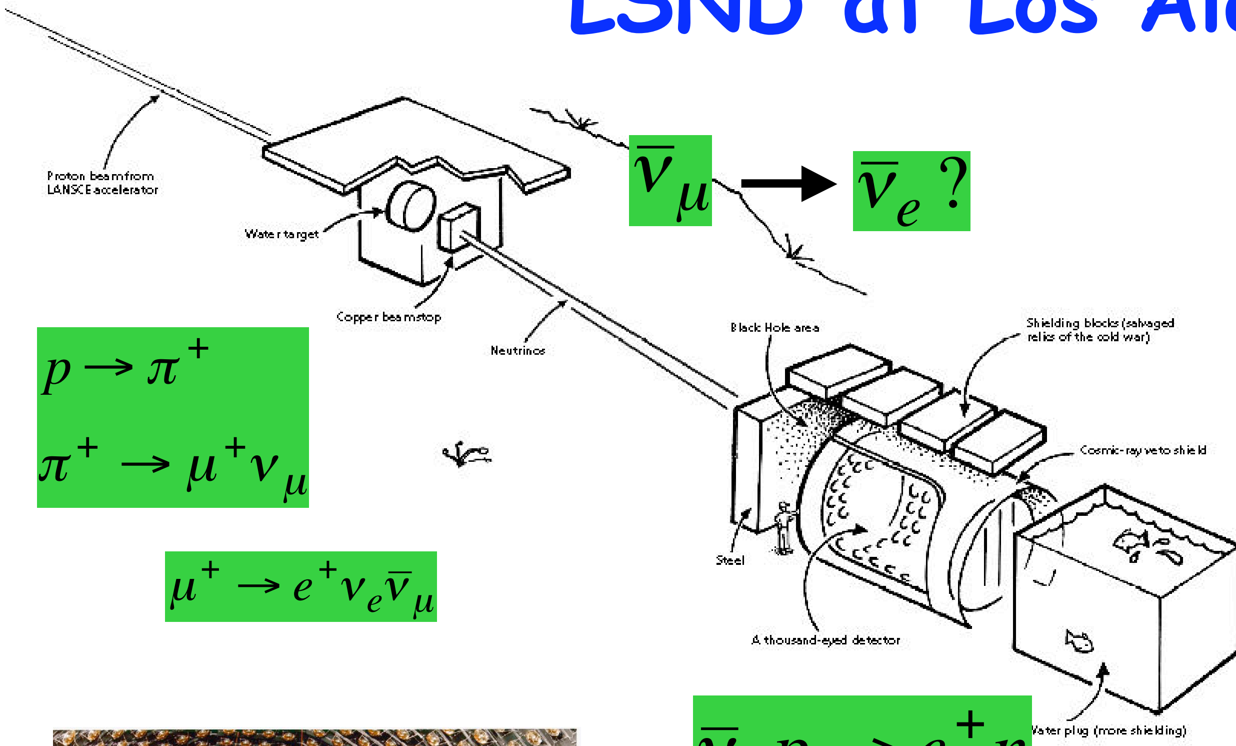


What do we know and how do we know it



Slide adapted from B. Kayser

LSND at Los Alamos



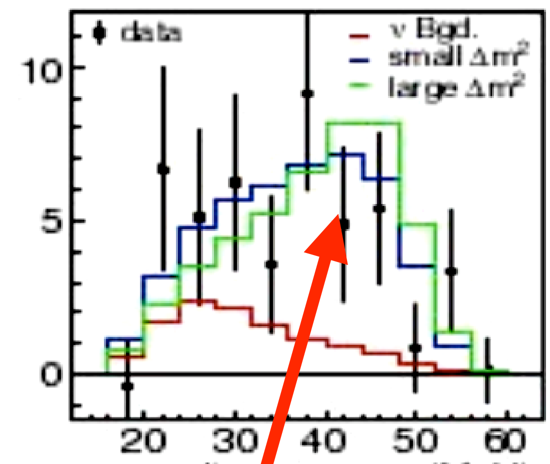
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$?

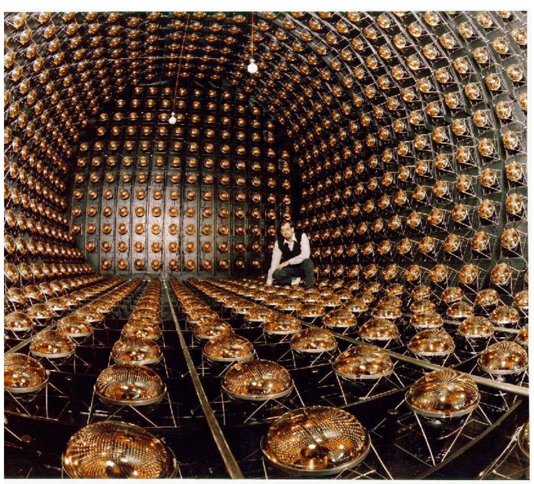
$p \rightarrow \pi^+$

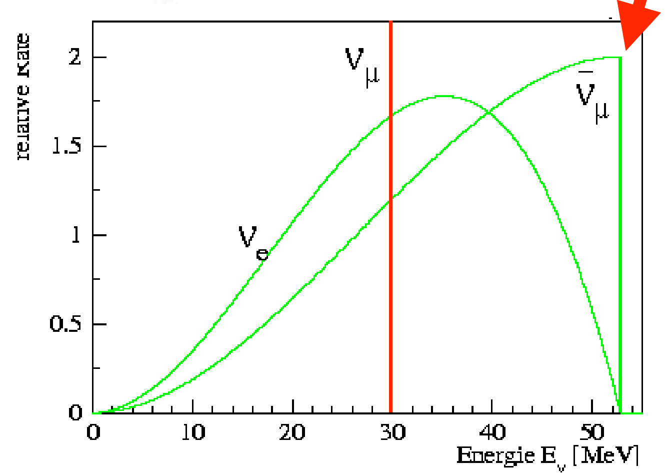
$\pi^+ \rightarrow \mu^+ \nu_\mu$

$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$

$\bar{\nu}_e p \rightarrow e^+ n$







The Open Questions

Neutrinos and the New Paradigm

- What are the masses of the neutrinos?
- What is the pattern of mixing among the different types of neutrinos?
- Are neutrinos their own antiparticles?
- Do neutrinos violate the symmetry CP?

Neutrinos and the Unexpected

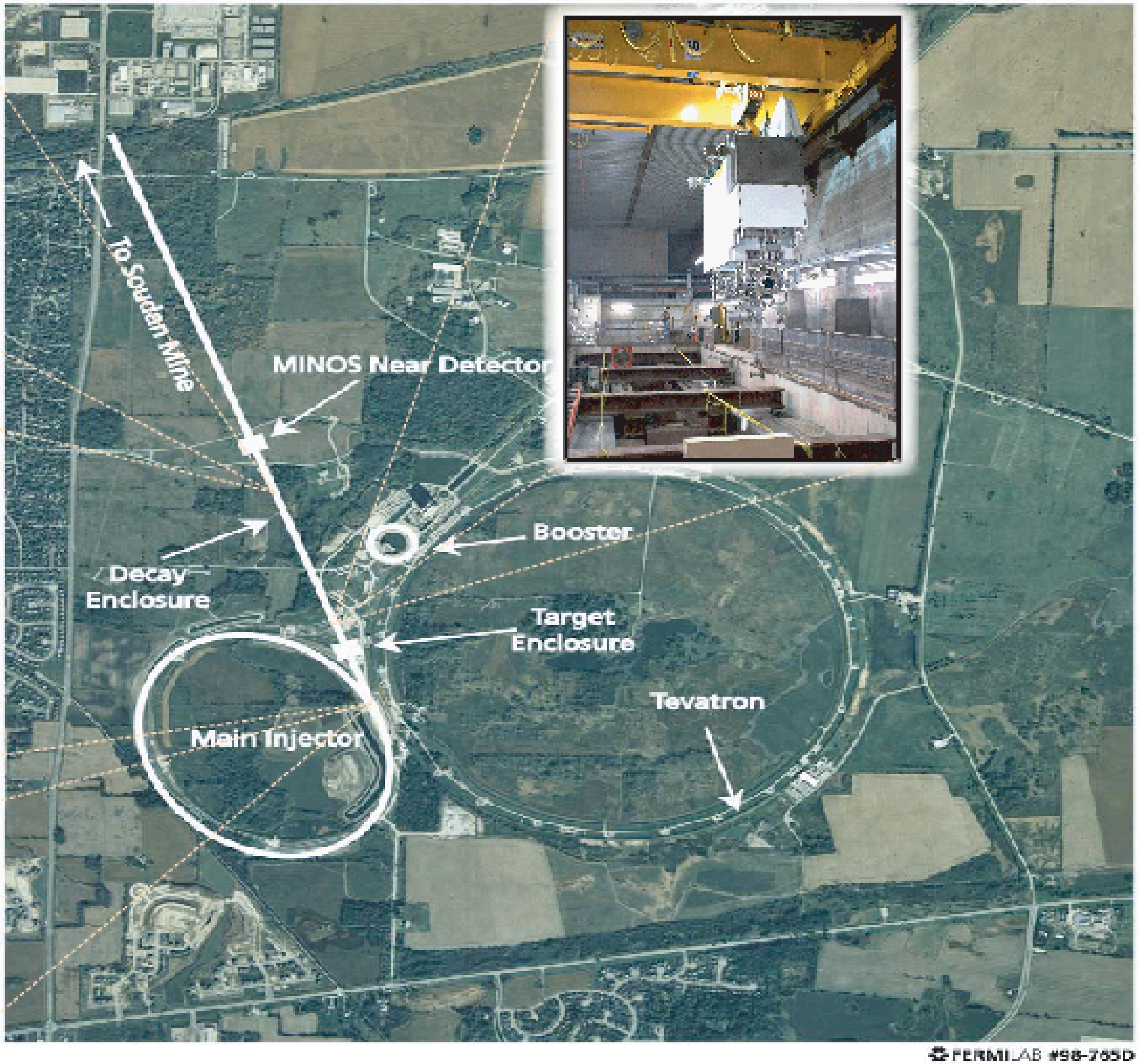
- Are there “sterile” neutrinos?
- Do neutrinos have unexpected or exotic properties?
- What can neutrinos tell us about the models of new physics beyond the Standard Model?

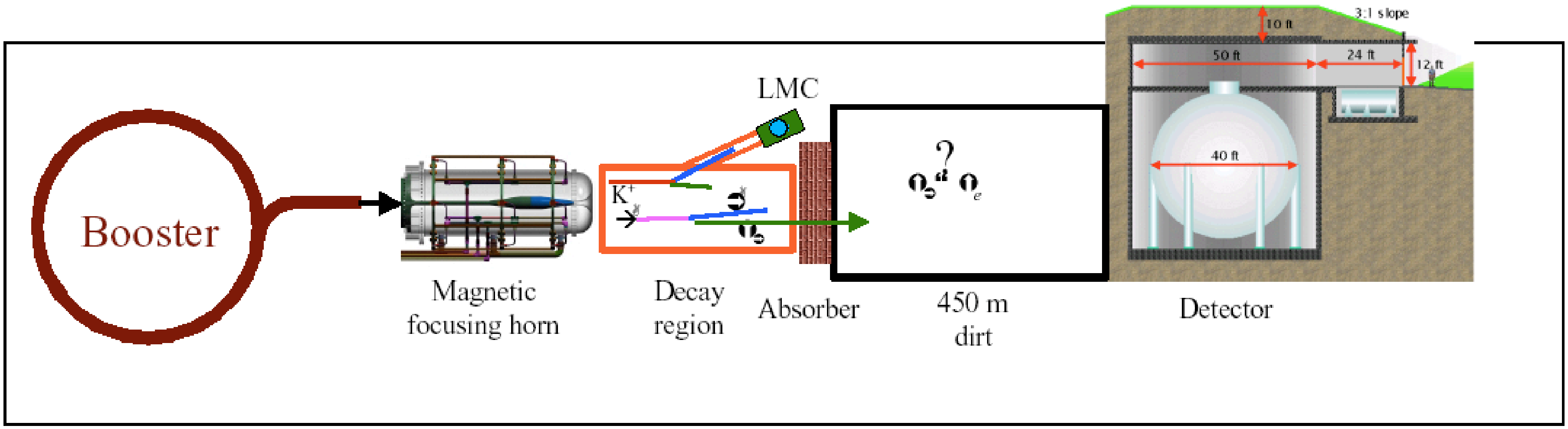
Neutrinos and the Cosmos

- What is the role of neutrinos in shaping the universe?
- Are neutrinos the key to understanding the matter – antimatter asymmetry of the universe?
- What can neutrinos reveal about the deep interior of the earth and sun, and about supernovae and other ultra high energy astrophysical phenomena?

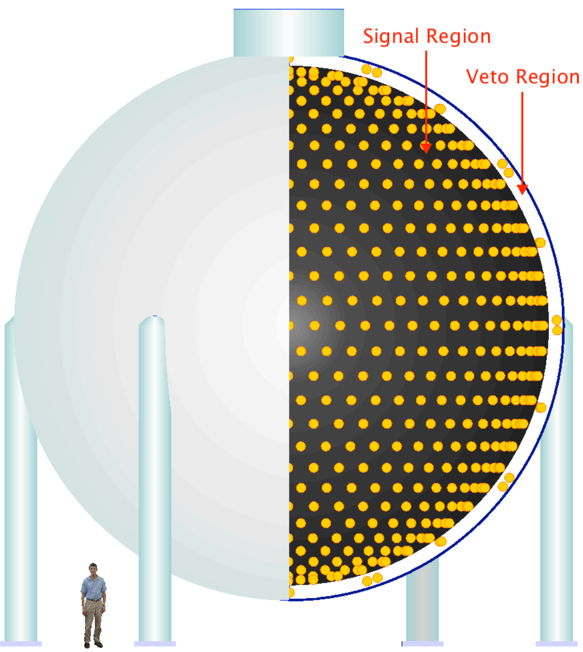
Neutrinos At the Main Injector (NuMI)

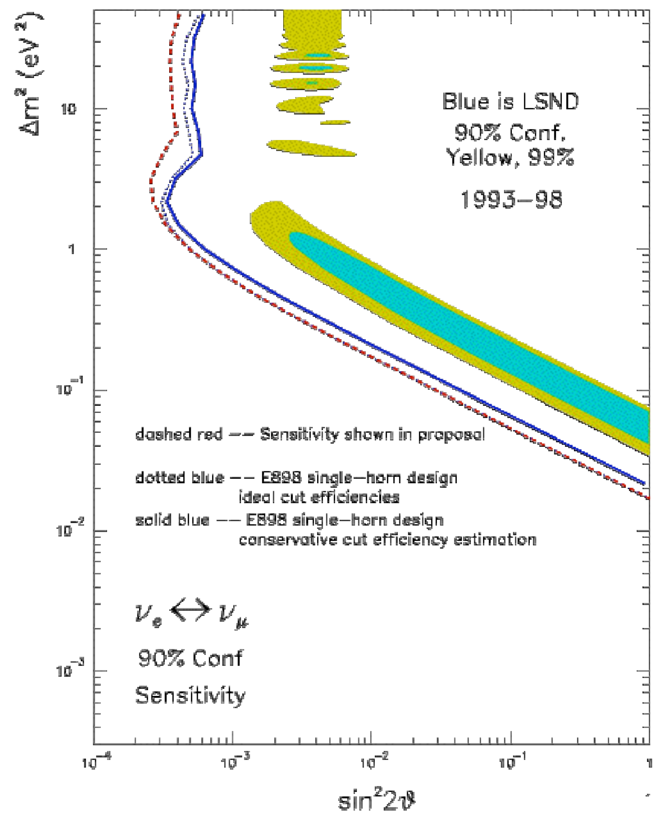
NuMI beam set to commision start of 2005

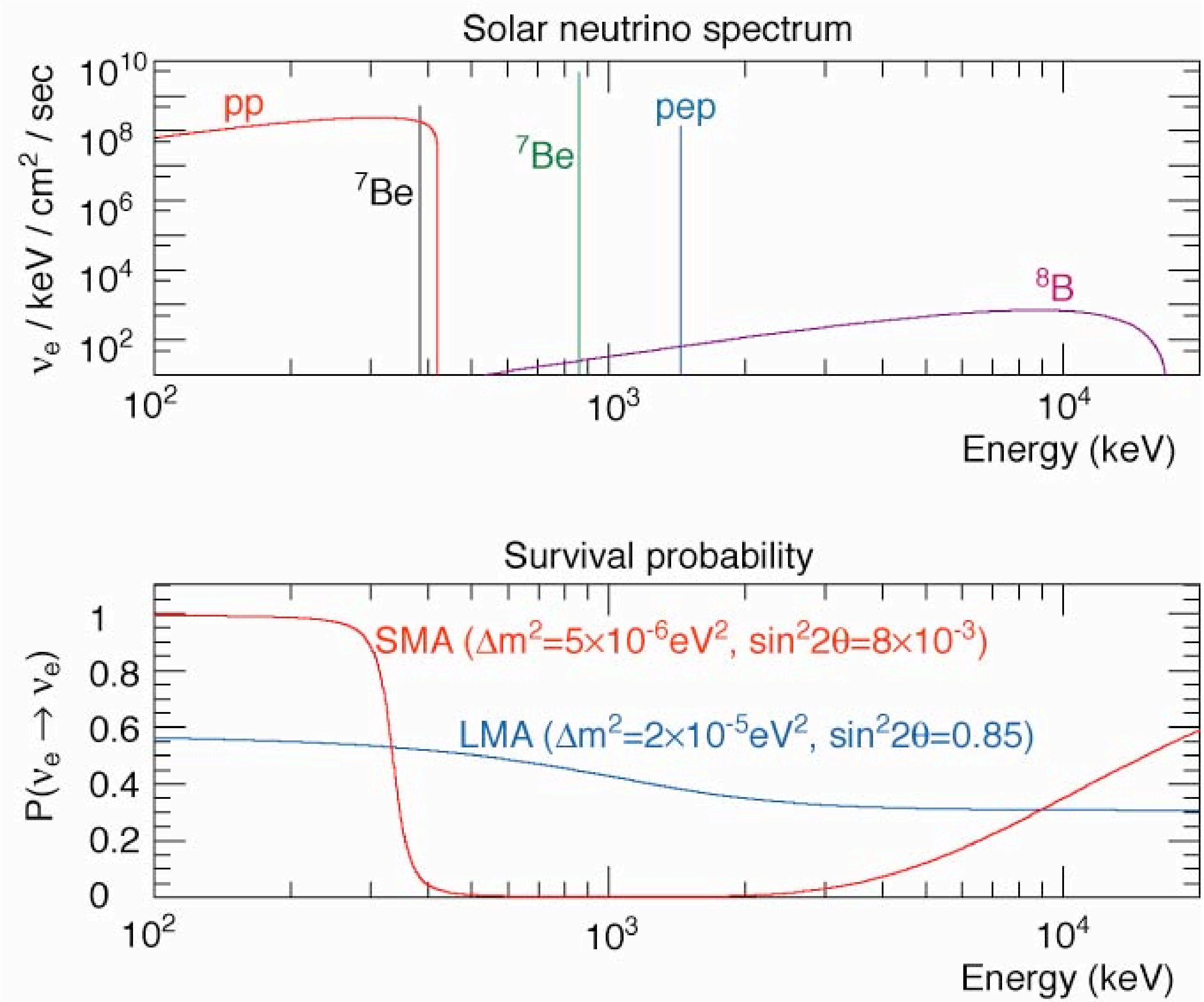




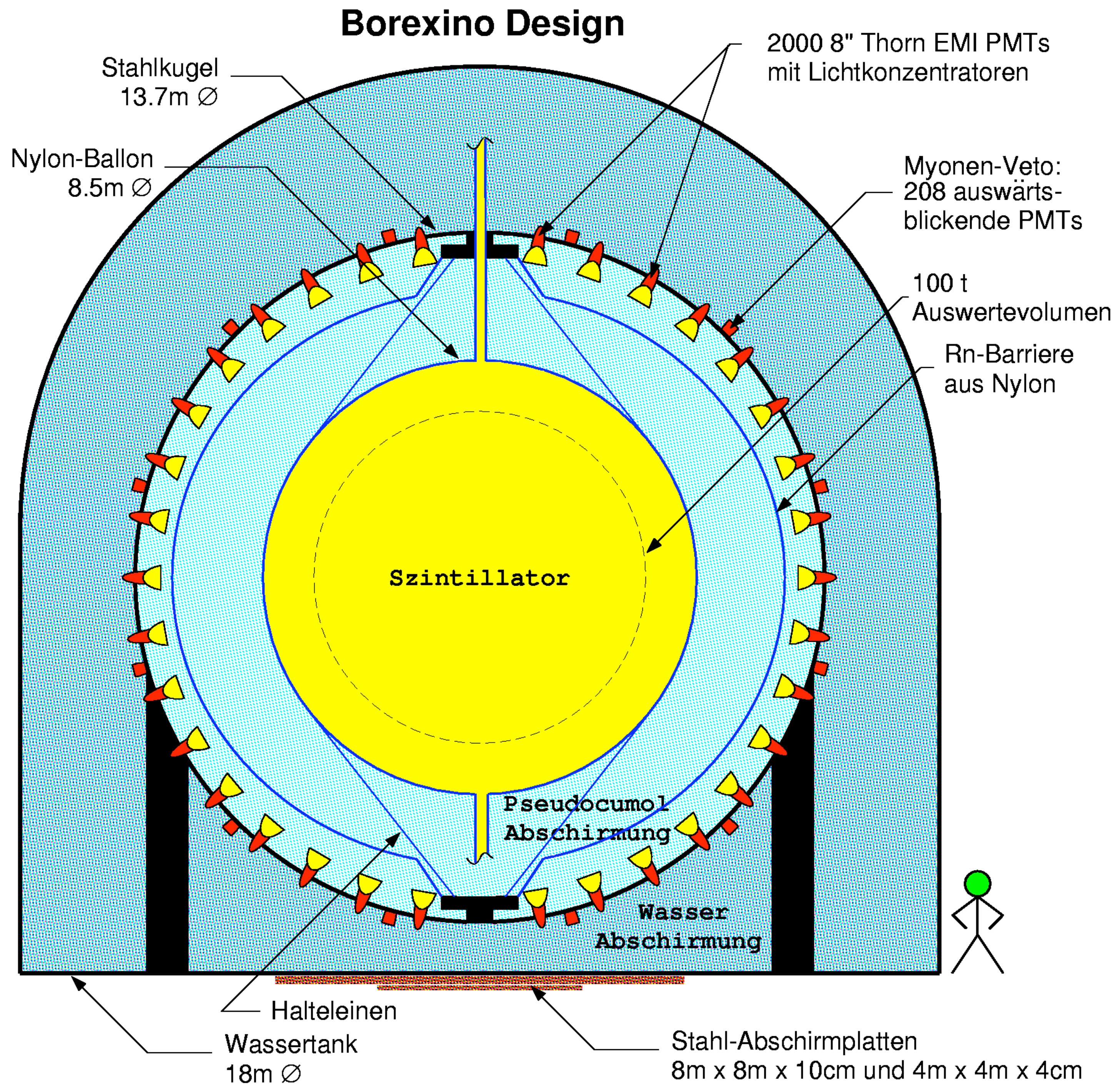
MiniBooNE Detector



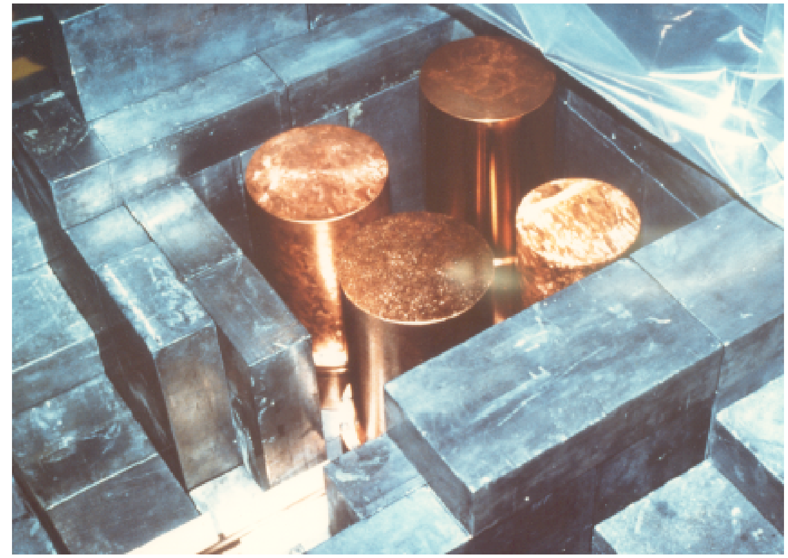




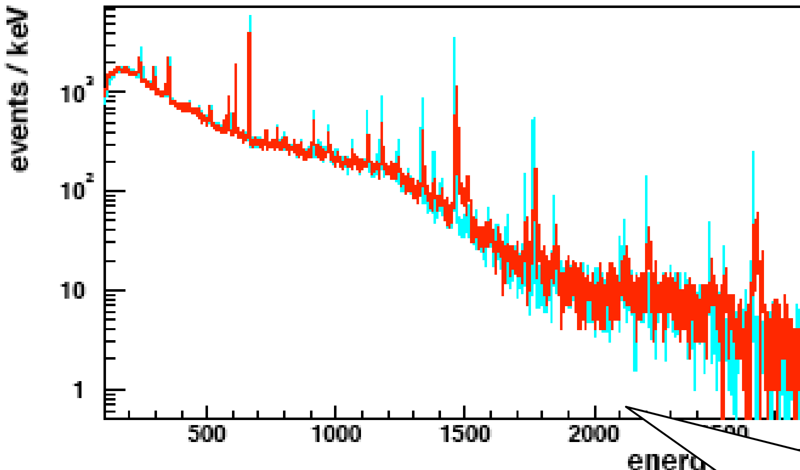
Solar neutrino spectrum
ν_e / keV / cm^2 / sec
10^{10}
10^8
10^6
10^4
10^2
pp
^{7}Be
^{7}Be
pep
^{8}B
10^2
10^3
10^4
Energy (keV)
Survival probability
$P(\nu_e \rightarrow \nu_e)$
1
0.8
0.6
0.4
0.2
0
SMA ($\Delta m^2=5\times10^{-6}eV^2, sin^2 2\theta=8\times10^{-3}$)
LMA ($\Delta m^2=2\times10^{-5}eV^2, sin^2 2\theta=0.85$)
10^2
10^3
10^4
Energy (keV)


Borexino Design
Stahlkugel
13.7m ∅
Nylon-Ballon
8.5m ∅
2000 8" Thorn EMI PMTs
mit Lichtkonzentratoren
Myonen-Veto:
208 auswärts-
blickende PMTs
100 t
Auswertevolumen
Rn-Barriere
aus Nylon
Szintillator
Pseudocumol
Abschirmung
Wasser
Abschirmung
Halteleinen
Wassertank
18m ∅
Stahl-Abschirmplatten
8m x 8m x 10cm und 4m x 4m x 4cm

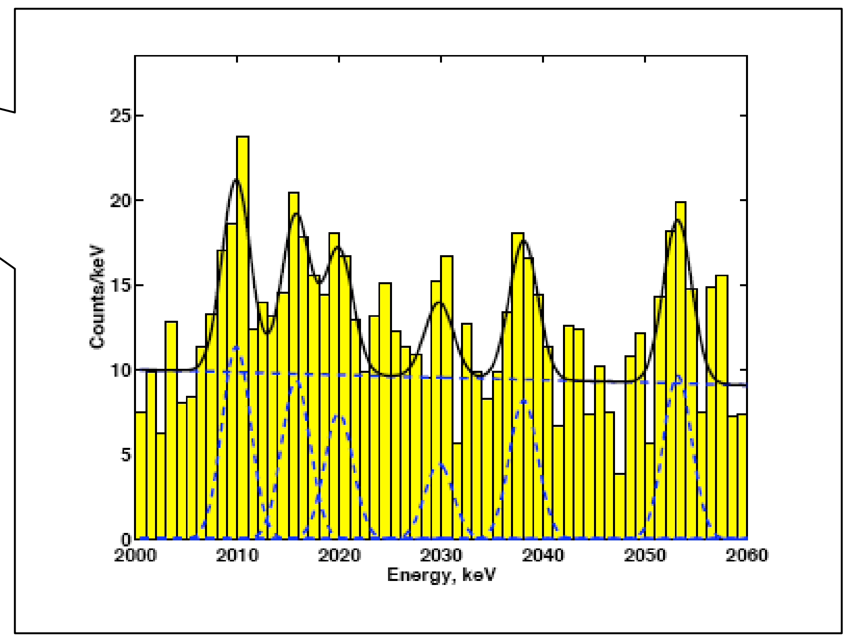
$0\nu\beta\beta$ in ^{76}Ge



5 detectors of overall 10.96 kg enriched to 86-88% in the $\beta\beta$-emitter ^{76}Ge



hep-ph/0403018



T = (0.69 - 4.18) x 10^{25} years (3 σ)

Majorana ν Mass

m_ν= (0.24 - 0.58) eV (3 σ)

$m_{\nu\ \mathrm{best}}$ = 0.44 eV

Double Beta Decay Experiments

Experiment	Isotope	Technique	Isotope Mass (kg)	Enriched	$Q_{\beta\beta}$ (MeV)	$<m_{ee}>$ (eV) 90%CL	Overhead (mwe)	Location
Heidelberg-Moscow	^{76}Ge	5 Ge crystals	9.9	86%	2.04	< 0.40	2700	Gran Sasso, Italy
IGEX	^{76}Ge	6 Ge crystals	~9	86%	2.04	< 0.44	2450	Canfranc, Spain
UCI	^{82}Se	TPC with foils	0.014	97%	2.99	< 7.7	290	Hoover Dam, US
ELEGANT	^{100}Mo	drift chamber - scintillators	0.20	94.5%	3.03	< 2.7	1800	Oto, Japan
Kiev	^{116}Cd	$CdWO_4$ crystals	0.09	83%	2.8	< 3.3	1000	Slotvinia, Ukraine
Missouri	^{128}Te	Geochemical	Te Ore	No	.87	< 1.5	N/A	N/A
Milano	^{130}Te	Cryogenic 20 TeO_2 crystals	2.3	No	2.53	< 2.6	2700	Gran Sasso, Italy
Cal-UN-PSI	^{136}Xe	High Pres. TPC	2.1	62.5%	2.47	< 3.5	3000	Switzerland
UCI	^{150}Nd	TPC foils	0.015	91%	3.37	< 7.1	290	Hoover Dam, US
NEMO3	^{82}Se, ^{100}Mo, ^{116}Cd, ^{150}Nd	drift chamber-scintillator	1, 10, 1, 1	Yes	3.0,3.0, 2.8,3.4	~0.1	4800	Frejus France
CUORICINO	^{130}Te	Cryogenic 56 TeO_2 crystals	11.5	No	2.6	~ 0.1	2700	Gran Sasso, Italy
GENIUS	^{76}Ge	400 Ge crystals	1000	Yes	2.04	0.01		Gran Sasso, Italy
MAJORANA	^{76}Ge	210 Ge crystals	500	Yes	2.04	0.02	≥ 4000	
CAMEO	^{82}Se, ^{100}Mo, ^{116}Cd	Borexino CTF	~1, 1, 1	Yes	2.99, 3.0, 2.8	~1		Gran Sasso, Italy
MOON	^{100}Mo	Scint+Foils	3400	No	3.03	0.03	≥ 2500	
CUORE	^{130}Te	Cryogenic 1020 TeO_2 crystals	210	No	2.53	0.02		Gran Sasso, Italy
EXO	^{136}Xe	High Pres. TPC	10000	Yes	2.47	0.01	≥ 2000	
DBCA-II(2)	^{150}Nd	Drift chamber	18	Yes	3.37	~0.05		Oto, Japan

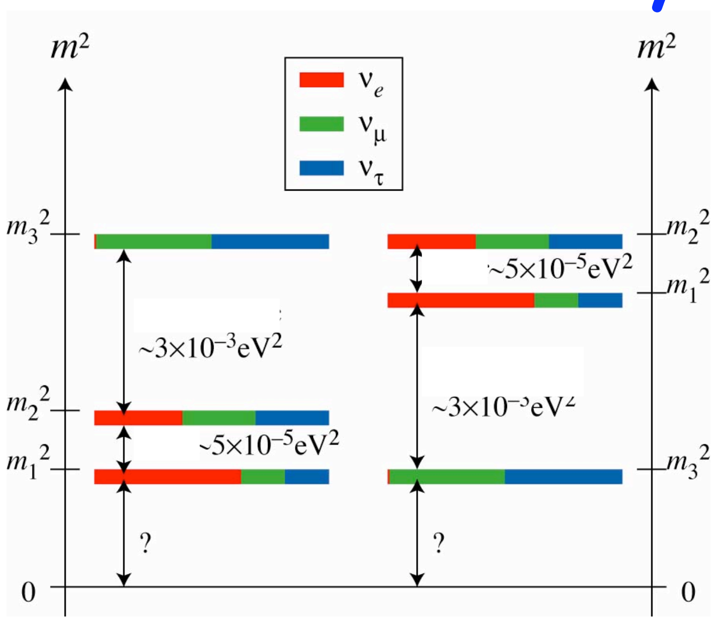
U_{MNSP} Matrix

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}$$

$\theta_{23} \sim 45°$ $\tan^2\theta_{13} < 0.03$ at 90% CL $\theta_{12} \sim 32°$

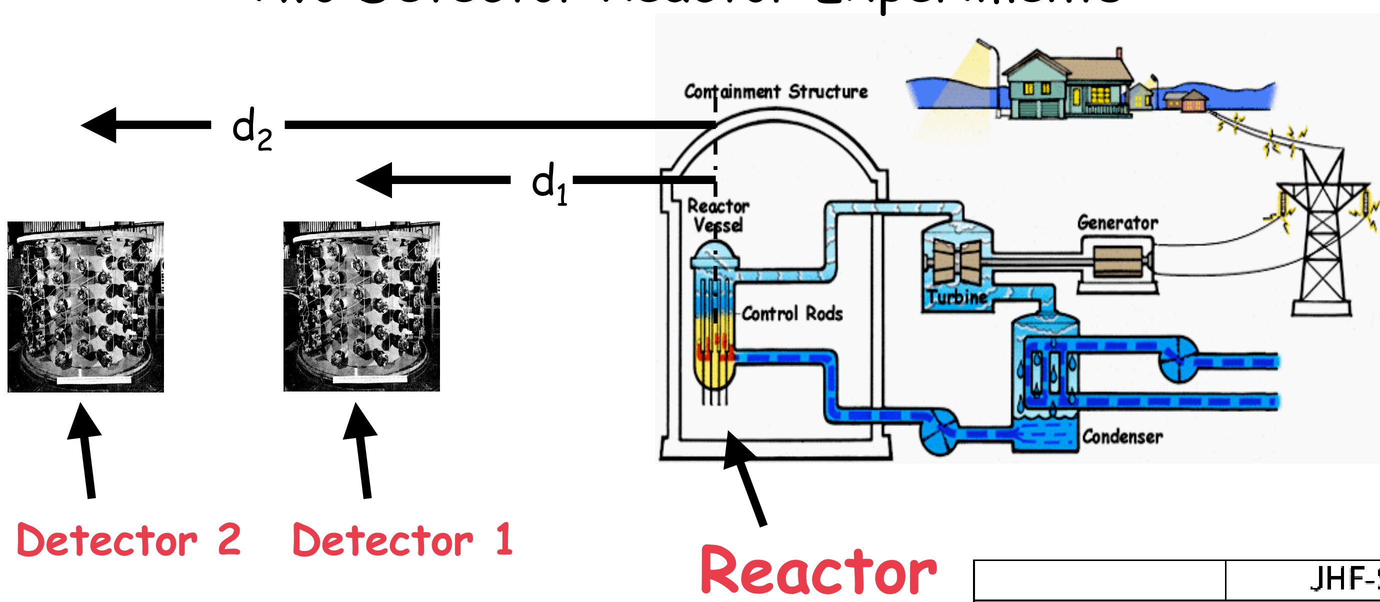
Mass Hierarchy



$$P(\nu_e \to \nu_\mu) - P(\bar{\nu}_e \to \bar{\nu}_\mu) =$$

$$16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$$

Two Detector Reactor Experiments



Off Axis Experiments at Accelerators

	JHF-SK	NuMI
Beam		
Baseline	295 km	712 km
Target Power	0.77 MW	0.4 MW
Off-axis angle	2°	0.72°
Mean energy	0.76 GeV	2.22 GeV
Mean L/E	385 km GeV^{-1}	320 km GeV^{-1}
Detector		
Technology	Water Cherenkov	Low-Z calorimeter
Fiducial mass	22.5 kt	17 kt
Running period	5 years	5 years

Solar Neutrino Experiments

		Fiducial Mass		Threshold, keV			BP00 Rates per year					
Expt.	Type	Tons	of	ES	CC	NC	pp +pep	^{7}Be	^{8}B	CNO	Event Eff. %	Start
Cl-Ar	Radioch.	135	^{37}Cl		814		14	72	363	26	16	1968
Kamioka	Cerenkov	680	water	7000					120		100	1985
SAGE	Radioch.	23	^{71}Ga		233		181	86	31	22	25	1990
Gallex	Radioch.	12	^{71}Ga		233		94	45	16	11		1991
SuperK	Cerenkov	22000	water	5500					10200		100	1996
GNO	Radioch.	12	^{71}Ga		233		94	45	16	11		1998
SNO	Cerenkov	2000	water	5000					1100		100	1999
		200	^{2}H		6400				10000		100	1999
		200	^{2}H			2223			5000		50	1999
Borexino	Scintillator	100	scintillator	250				20000				2001
KamLAND	Scintillator	1000	scintillator									2001
ICARUS	L Ar TPC	600	Ar									
HERON	L He rotons, Scintillator	5	He	100			3025	1500	2	125	80	
HELLAZ	Gas TPC	7	He	180			4000					
LENS	Scintillator	2.5	^{176}Yb		301,445		190	145	10	40		
MOON	Scint+Foils	3.3	^{100}Mo		168		409	129	14	34	20	
CLEAN	Scintillator	12.5	Ne	100			9000					
Iodine, Cl	Hybrid		I, Cl									
GaAs	Ionization		^{71}Ga									
LiF	Bolometer	0.9	^{7}Li		862	487	27	29			100	